Solar Energy Technology
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Lecture - 31
The Phi bar f chart Method (Contd.)

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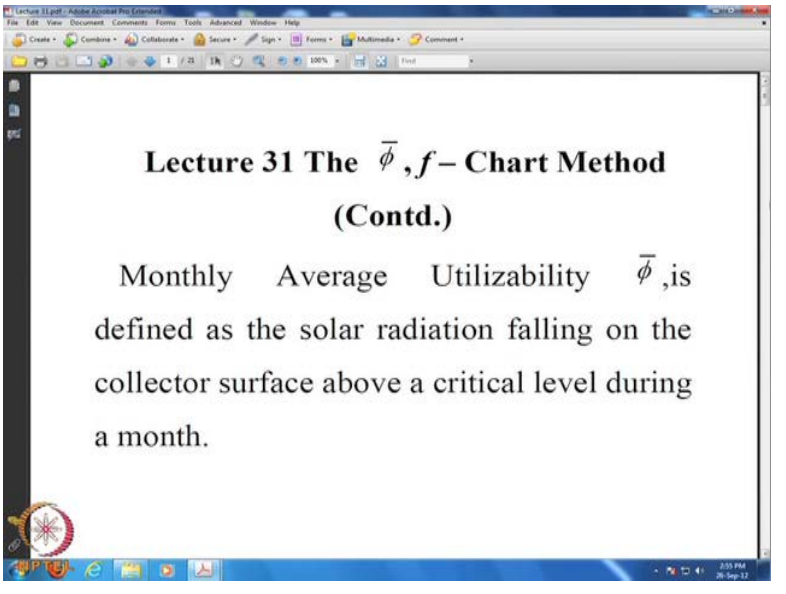

We shall continue with the phi bar, f-chart method for the sake of continuity and also to reinforce that the concepts, I am prepared to have little bit of repetition. So, this is an important method as well as an important concept.

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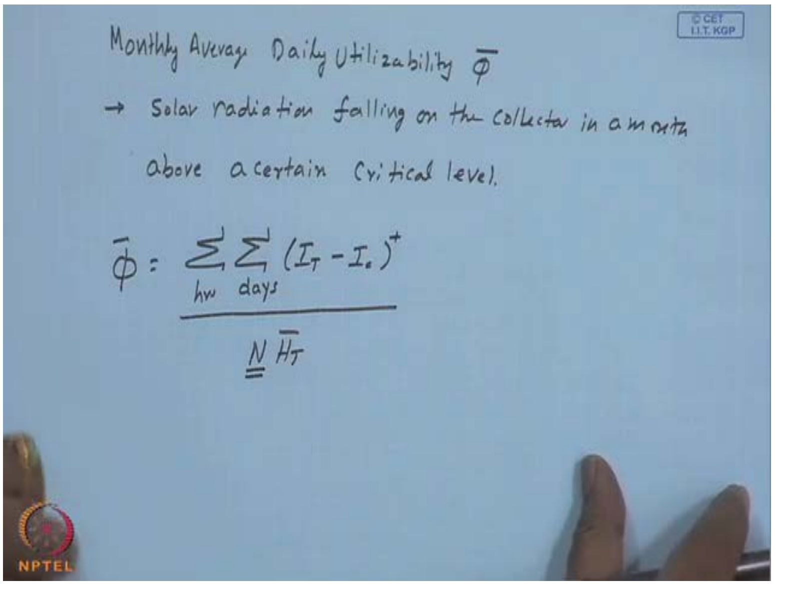

First, we define monthly average daily utilizability phi bar. This is the solar radiation falling on the collector in a month above a certain critical level. So, this symbolically we have written it as phi bar is summation over the days, over the hours and I T is the solar radiation falling on the collectors surface and I c is a critical radiation level times N into H T bar which is a monthly average daily radiation on the tilted surface multiplied by the number of days in the month.

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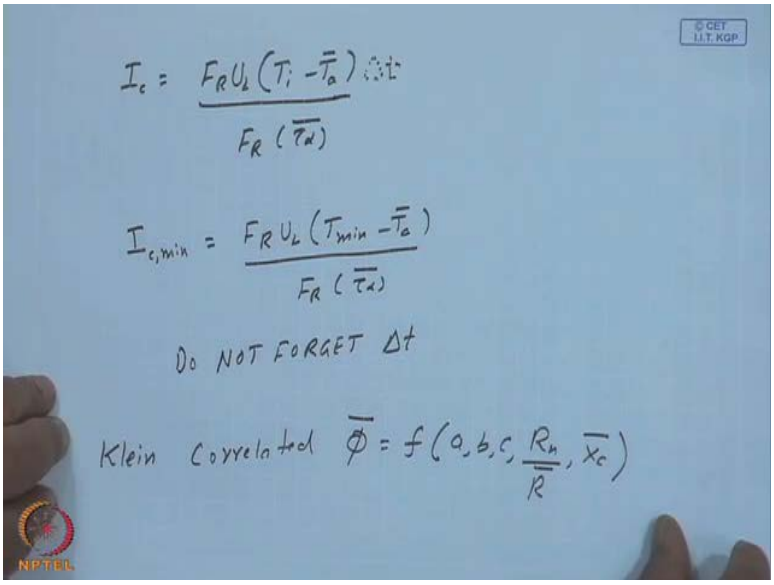

And the critical radiation level, corresponding to an inlay temperature of I c is defined as F R U L times T i minus T bar a as for upon F R T alpha bar and you should remember here is a hidden delta t which will indicate the time scale per which this is calculated. So, you have in terms of the minimum temperature above which energy delivery is designed. The same thing can be re-written as F R U L T minimum minus T a bar by F R tau alpha bar, where T a bar is the monthly average daily ambient temperature, U L is the overall heat loss coefficient, tau alpha bar is the monthly average trans of certain product and f bar is the collector heat remover factor.

So, I have again here emphasized or do not forget time delta t, otherwise this would be inverts and this will be in non-dimensional form, ok. So, we already stated that Klein correlated phi bar as a function of tri-constant a, b, c and there is geometric factor R n by R bar and a non-dimensional critical radiation level X c bar for south facing flat plate collectors.

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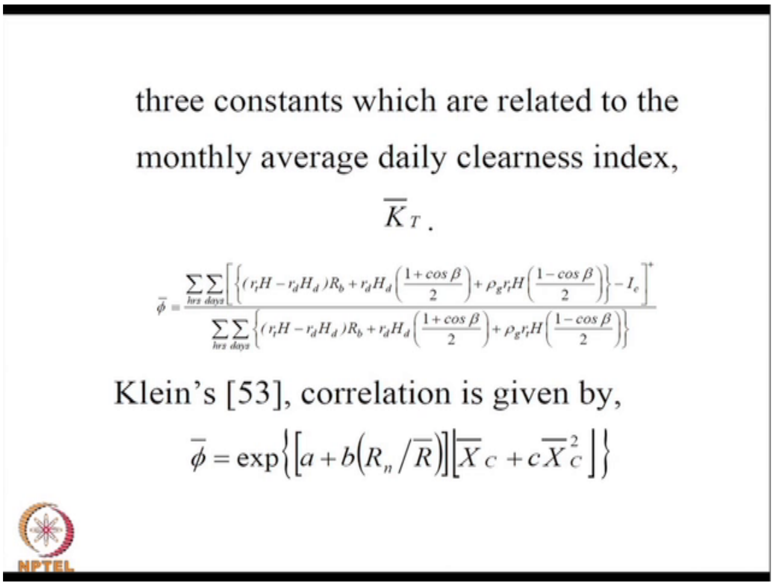

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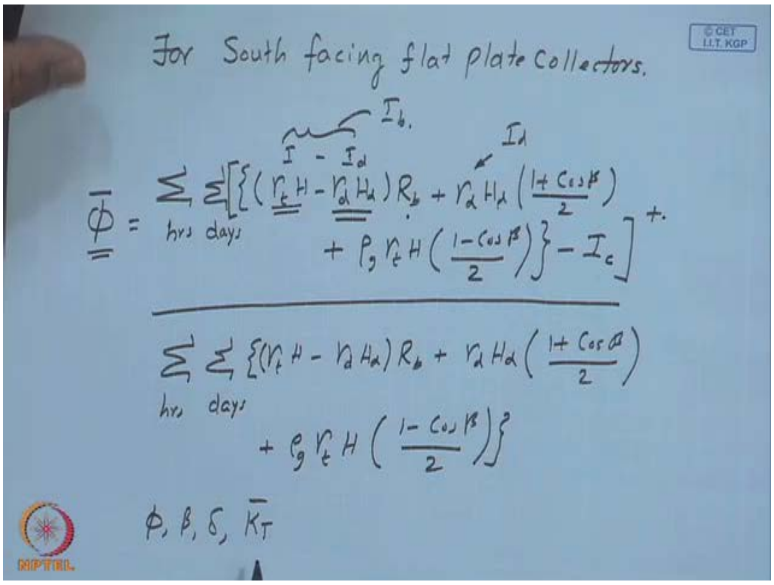

So, these three constants which are related to the monthly clearness index K T bar. So, you can rewrite this in a long form phi bar which I think this equation can be seen on the screen. However, I shall write it down here over hours over days r t into H minus r d into H d times R b plus r d H d 1 plus cos beta by 2 and then plus rho r t into H into 1 minus cos beta by 2.Then, we have got curly brackets minus critical level I c, then the square bracket with a superscript plus upon over hours. I should explain each term and then it becomes very easy for you to remember the basis on which we have written this, times R b plus r d H d times 1 plus cos beta by 2 plus rho r t into H times 1 minus cos beta by 2 curly bracket close.

So, this r t into H is nothing, but r d into H d is nothing, but I d. So, this makes it I minus I d which is nothing, but I b R b direct variation that multiplied by the tilt factor and r d into H d is again nothing, but I d times 1 plus cos beta by 2. R t into H is I multiplied by rho. The ground reflectance will give me the ground reflected component multiplied by the corresponding view factor 1 minus cos beta by 2 minus I c superscript plus indicates only the positive part is to be taken whenever this quantity is negative. It shall be (()) as 0. The denominator is nothing, but the total solar radiation falling on the collector surface over the month which we calculate each hour.

So, in other words, you can generate the monthly average daily utilizibility using r t and r d correlations at number of latitudes beta and delta even if you put gamma equal to 0, ok. So, this will give you a control over and of course, different K T bars. So, you can do that and hence, develop a correlation. Of course, this r t and H and r d and H d will bring in certain differences between the data values for a corresponding location and actually, the way the numbers that are obtained from this calculation.

However, we are making some sort of an error in both numerator and the denominator and hence, the overall error may not be much and further, it will show the clear functional dependence on phi beta and delta K T bar instead of scatter if you use only the data. This is not to say that it does not have to be verified against data. It needs to be verified against data. However, this is one way of generating in a control fashion for all the variables that will be looking for, namely phi beta delta and K T bar.

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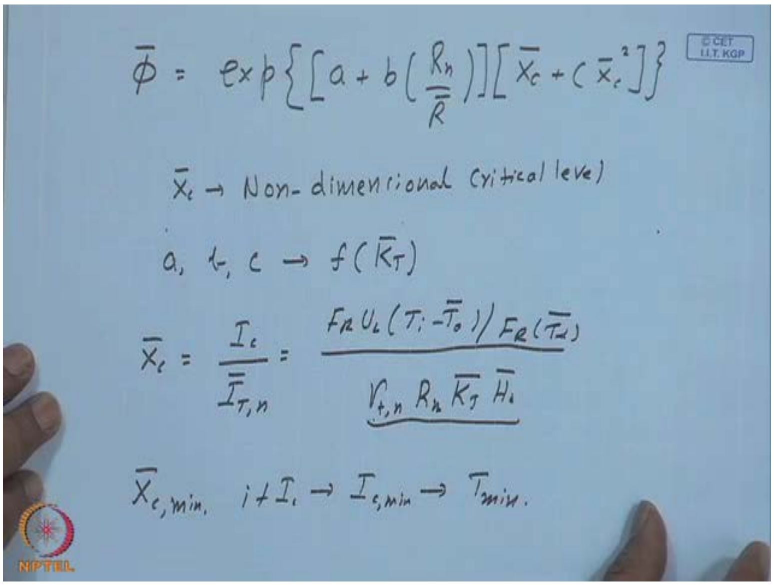

So, the Klein's correlation has the form exponential a plus b R n by R bar times X c bar plus C X c bar square. So, this is a non-dimensional critical level. X c bar is the non dimensional critical level and a, b and c are constants which are expressed in terms of a, b and c are function of monthly average daily clearness index K T bar. This X c bar is defined as critical level by I T noon time on the average day of the month which shall be equal to F R U L into T i minus T a bar by FR tau alpha bar by r t n R n K T bar H 0 bar.

You can see that this is nothing, but the noon time radiation K T bar into H 0 bar is going to give you H bar that multiplied by R noon time will be I at the noon time multiplied by the corresponding tilt factor for the orientation of the collector that is constant. So, it is customary to sometimes call X c bar as X c bar minimum if I c corresponds to I c minimum corresponding to T minimum, the temperature above which energy delivery is desired analogously.

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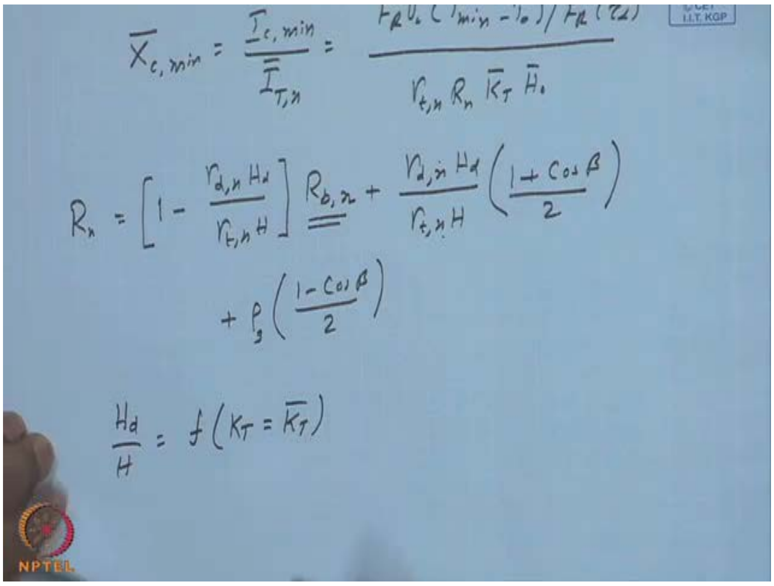

You can write X c bar minimum I c min by I T bar noon equal to FRU L T min minus T a bar by FR tau alpha bar by r t n R n K T bar H 0 bar. I suppose, you remember these symbols that we had discussed number of times in the previous classes. K T bar is the monthly average clearness index H g bar, H 0 bar is the monthly average daily x radiation and R is the tilt factor and r t is I by H, the Collares Pereira Robles form of expressing the hourly radiation as a ratio of with respect to the daily radiation H bar.

Now, to complete R n, once again we use r t and R n correlations 1 minus r d n upon H d upon r t n into H R b at the noon time plus r d noon by H d by r t n H times 1 plus cos beta by 2 plus rho into 1 minus cos beta by 2. This you may call it rho. So, once again this is nothing, but 1 minus I d by I. This is I d by I because we equate R n into I n is equal to this much and brought or divided throughout this is the noon time tilt factor for the (()) R b at noon and here, I also emphasise that H d by H is calculated as daily clearness index with K T numerically equal to K T bar.

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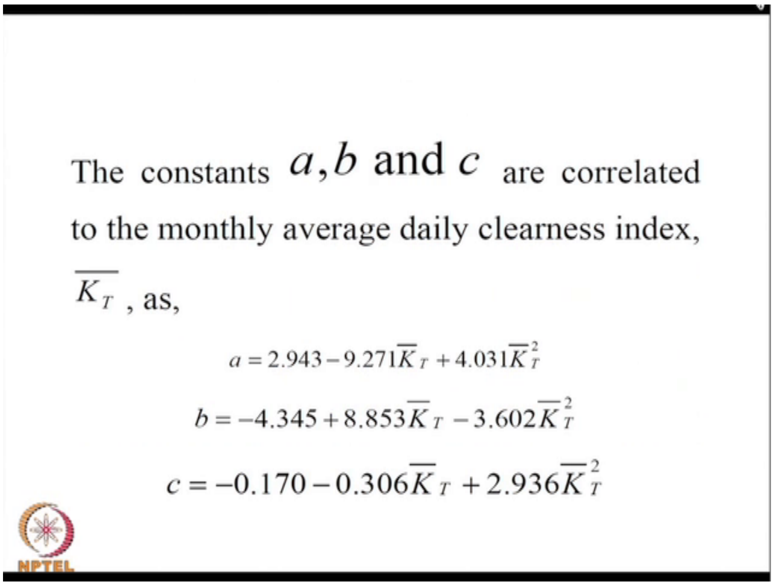

For a number of reasons that this is supposed to have worked better, consequently this has been adopted.

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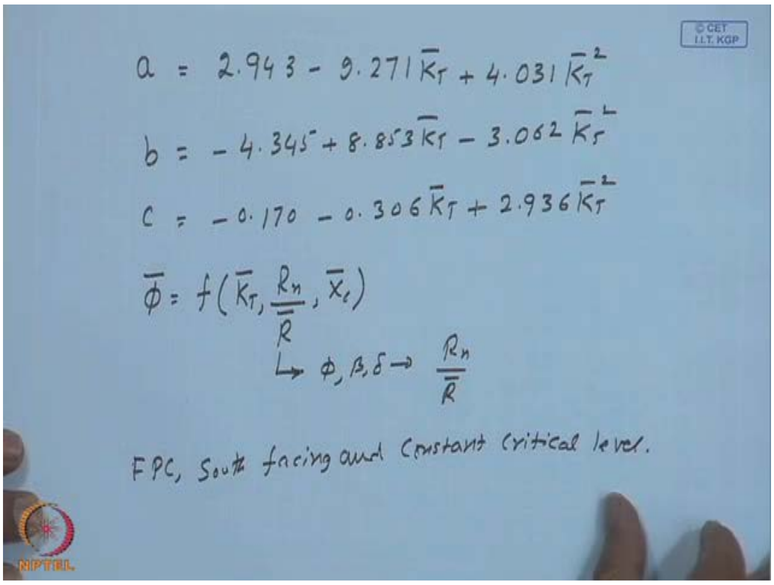

The constants a is 2.943 minus 9.271 K T bar plus 4.031 K T bar square and b is minus 4.345 plus 8.853 K T bar minus 3.062 K T bar square and c is minus 0.170 minus 0.306 K T bar plus 2.936 K T bar square. We should work it a problem towards the end of this lecture, may be the next one and then you will understand the orders of magnitude of constant a, b and c.

So, now we have got a phi bar function of essentially K T bar which will decide this constant a, b and c and instead of phi beta and delta, you have got R n by R bar and the non-dimensional critical level X c bar. So, this is some sort of simplification. All phi, beta, delta is combined into one single factor R n by R bar. So, this has got as I said that it is valid only for flat plate collectors south facing and constant critical level. There were times Collares Pereira Robles to include concentrating and non-south facing are precious.

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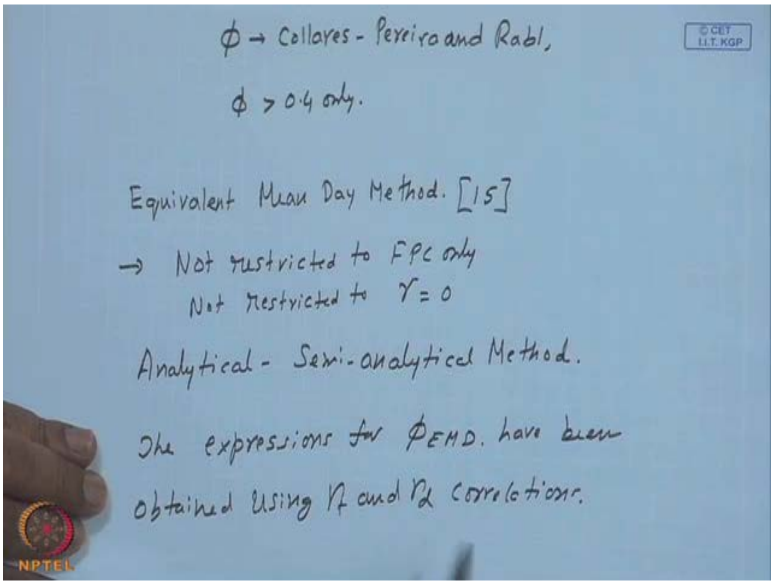

However, that is restricted to when the monthly average utilizability, he calls it a phi is slightly different definition Collares Pereira and Robles. This is valid for phi greater than 0.4 only. In other words, at low utilizability, the correlation does not work. So, the argument sometimes given is that solar collectors are likely to be efficient, technologically viable only of the utilizability high.

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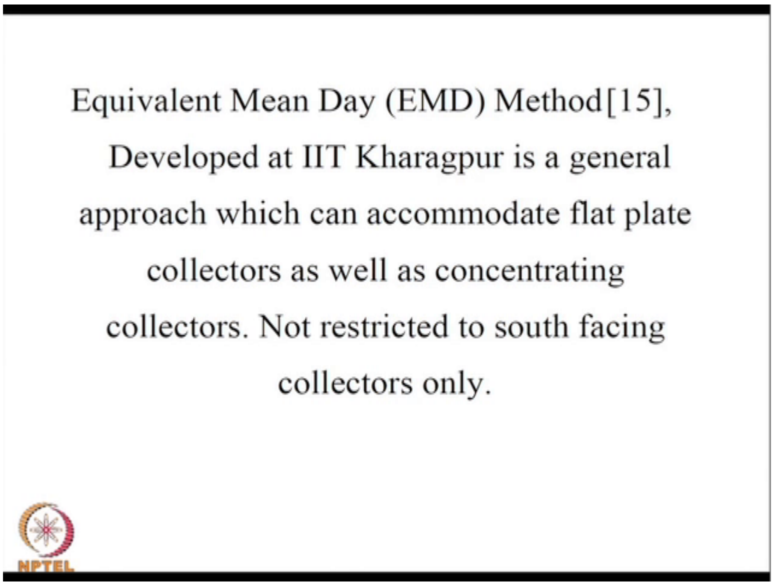

So, a method to evaluate utilizability when it is higher is acceptable. Finally, the work at IIT, Kharagpur proposed an Equivalent Mean Day method. This is available in a journal paper which I have given the reference and this is methodology. In fact, the working also is not restricted to FPC only and not restricted to gamma is equal to 0.

So, the collector orientation can be general and it can accommodate the concentrating collectors, and it is who may call it analytical or depends upon purest the expressions for utilizibility and the Equivalent Mean Day which I will call phi EMD have been obtained using R t and R d correlations. I shall elaborate this little later. Before that, I would also like to point out variable critical level.

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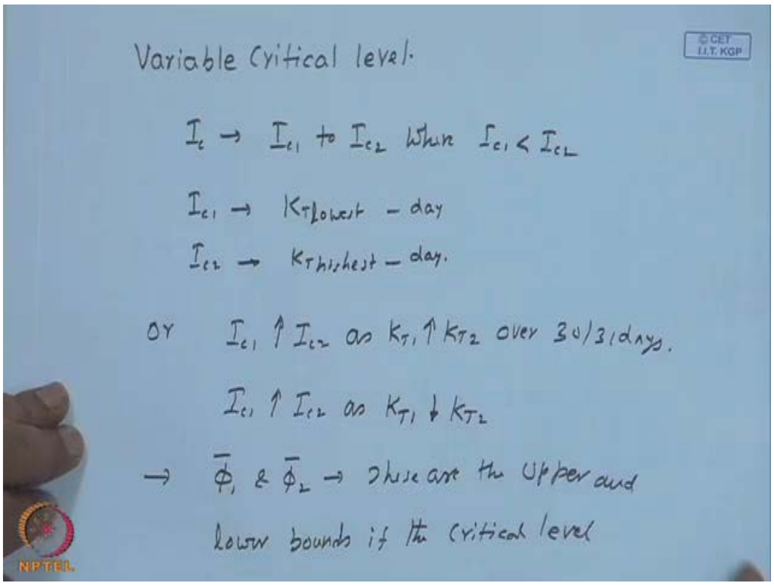

So, if the critical level varies every day, there is no simpler way of calculating except calculating each day, but if you look at from the middle date of point of view, I c may vary from I c 1 to I c 2, where I c 1 is less than I c 2 and I c 1 may be on K T lowest and I c 2 may be K T highest day. In other words, broadly you may say that because of the solar radiation being higher or lower or ambient temperature correspondingly being higher or lower. I can have scenarios of variable critical level varying minimum value to maximum value along with the change monotonically with the clearness indices distribution for that particular month, or that is I c 1 increasing to I c 2 as K T 1 increases to K T 2 over 30 or 31 days.

The other extreme scenario is I c 1 increasing to I c 2 as KT 1 decreases to KT 2. So, in other words, the highest critical level occurs at the lowest clearness index and the lowest critical level occurs with the highest clearness index. So, if we can calculate, so this will be to some phi 1 and phi 2 or phi bar 1 and phi bar 2.

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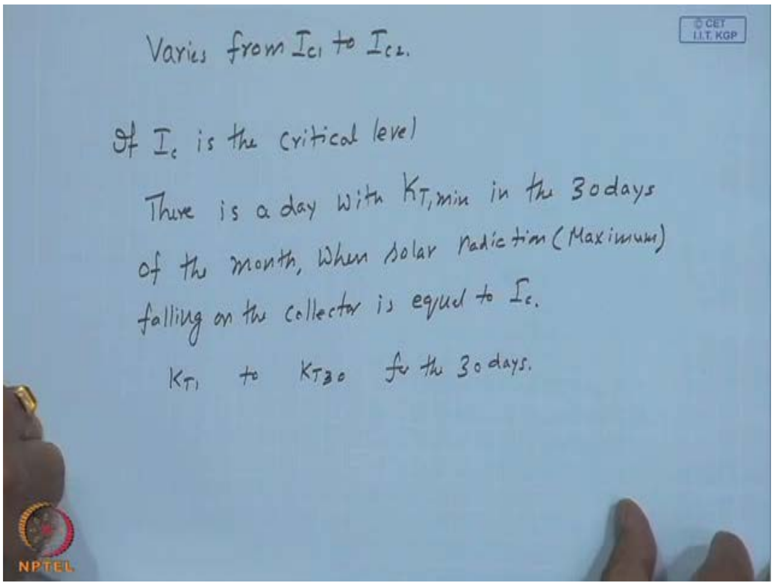

So, these are upper and lower bounds if the critical level varies from I c 1 to I c 2. I do not make any attempt to how to take care of I c 1 and I c 2 is varying, but nevertheless an upper monthly average daily utilizability and a lower monthly average daily utilizability can be obtained if we know that the critical level is varying from some low value I c 1 to I c 2. It may or may not necessary occur at the highest critical level, highest clearness index or lower critical clearness index, but if it does, I can produce two numbers and then these two numbers actual utilizability will fall somewhere in between. This has been verified and this can be easily verified by taking a number of distribution of these critical level of radiation varying from, let us say 200 watts per meter square to 400 watts per meter square, right.

Over I need random choice and uniformly varying with the clearness index or decreasing or increasing as clearness index increases, then you will have three numbers and any random choice will lie in between the two extremes as I have mentioned. So, coming back to equal and mean day by the way can be accounted this method because basically you make only day in calculation. What we try to do is, if I c is the critical level, there is z day with K T min in 30 days of the month when solar radiation maximum in the day falling on the collector is equal to I c. So, this maximum can be at noon time.

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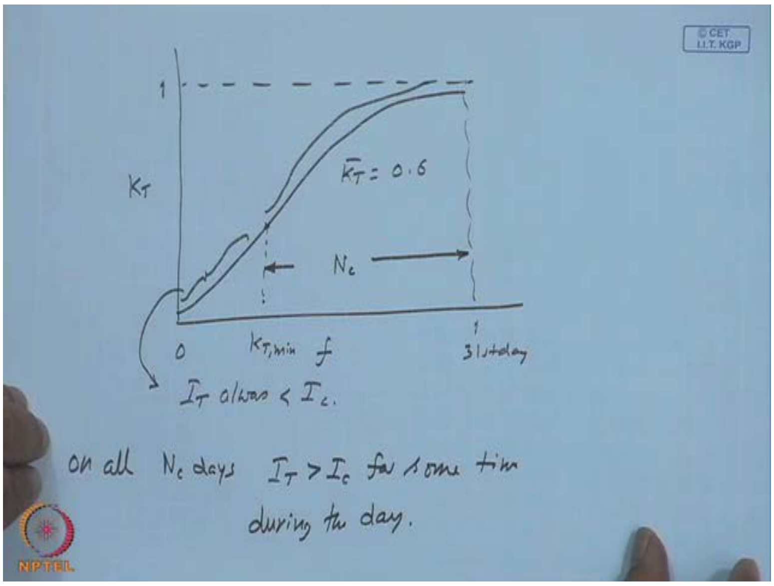

In other words, if I have got K T1 to K T 30 for 30 days whose distribution according to Lui and Gord Ankers cumulative frequency versus K T for a given K T bar say 0.6. This approximately 1 and this is my K T minimum. So, this much fractional time, I T always is less than I C. In these fractional times or the number of days, this one is accumulated to frequency or it can be considered as 0th day and 31st day. So, in these N c days on all I T is greater than I c for sometime during the day.

So, in identifying K T minimum, I said the maximum radiation instead of the noon time radiation because it can take care in principle announce of his phase as well as concentrating collectors.

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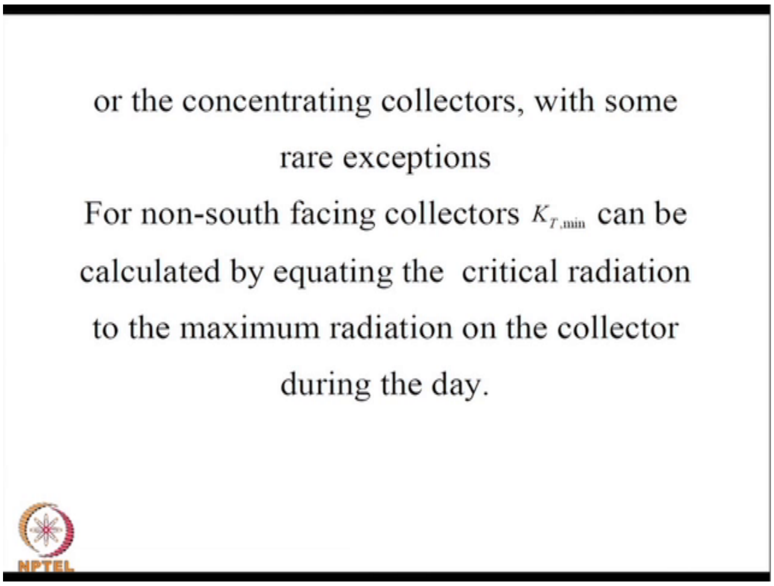

Concentrating collectors by the way, most of the time, it is symmetric and maximum occurs at the solar noon time only except in the third mode of a tracking, where the radiation act noon time may be lower than at some other time because of that becoming almost a horizontal approacher at the noon time.

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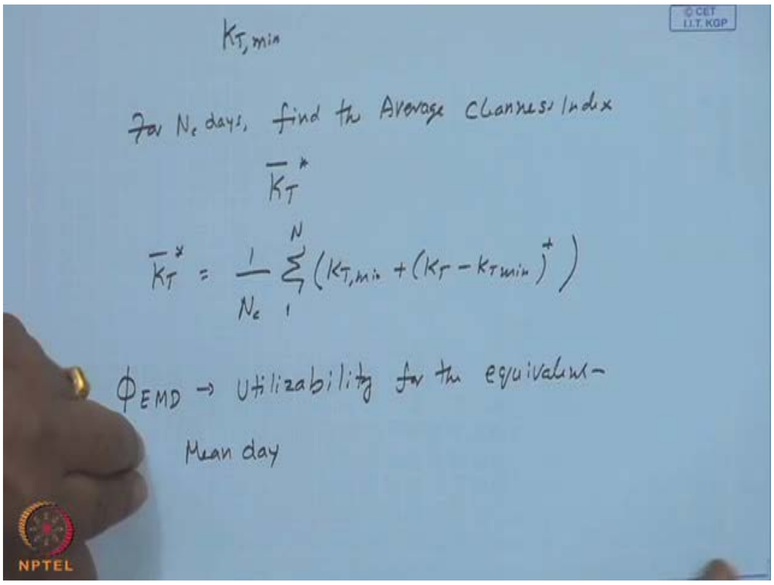

So, we identify this K T min. Then for the N c days, find the average clearness index which I will call it K T bar star. So, K T bar star equal to 1 upon the number of days above which the clearness index is below K T above KT minimum. All the 1 to N is K T min plus K T minus K T minimum superscript plus whole thing. This is only a clumsy way of mathematically putting, I am just finding out the clearness indices of the days with K T greater than K T minimum and take the average, so that if this is negative, it will be 0. Only K T minimum will be there. If this is positive, then that will be contributed to KT minimum that is the ordinate above the K T minimum value. That is all, nothing else.

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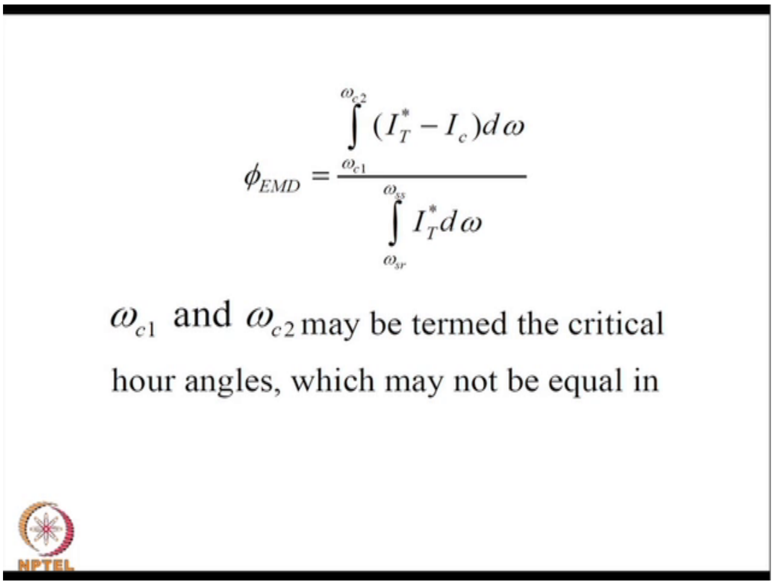

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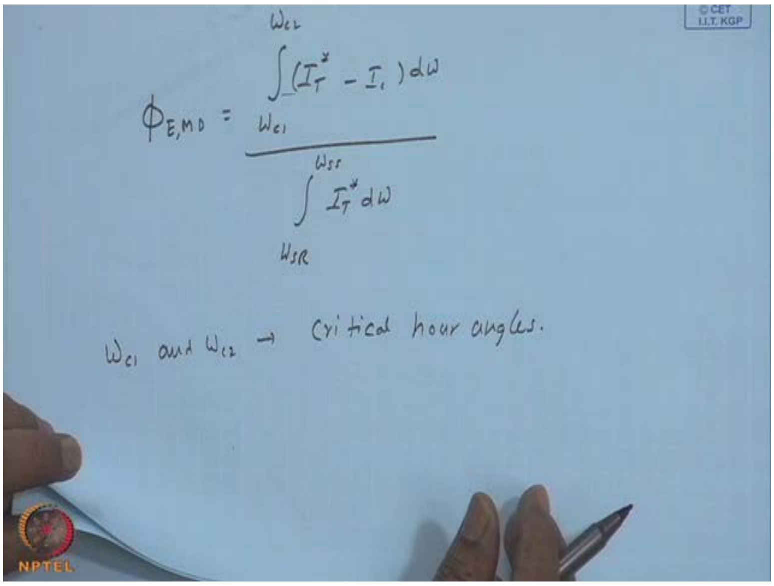

So, the phi EMD is the utilizability for the equal and mean day one can express because it is a single day. I can do it omega c 1 to omega c 2 of I T star minus I C d omega by integral apparent some days over angle to apparent sunset over angel of I T star d omega. The whole area is there is no super script plus sign over here. So, I can separate I T star and I C and do it integration and I C being a constant, it is nothing, but omega c 2 minus omega c 1. Omega c 1 and omega c 2 which I shall call the critical hour angles which may or may not be equal to magnitude wise depending upon whether it is south facing or non-south facing collector.

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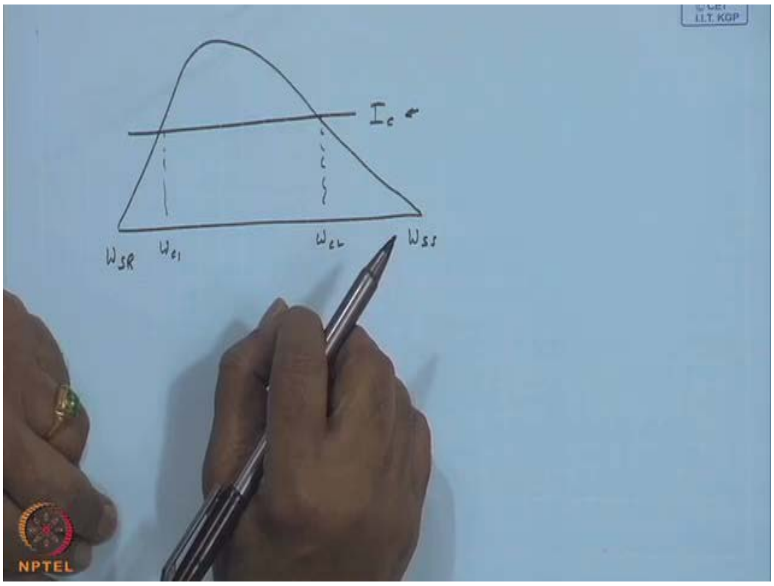

Pictorially if you have a, let us say gamma is equal to 0. This is omega SR, this is SS and this is I C. So, this will be omega c 1 and this will be omega c 2. So, write down the equation for I T for the appropriate orientation equate to the number I C and solve for the omega. You will get two values which will be omega c 1 and omega c 2, right. So, in this zone is I T star always greater than I C by hour definition because I T star is the solar radiation on the average day of the month, ok excluding those days clearness index lower than K T minimum for which there could be always I T lower than I C.

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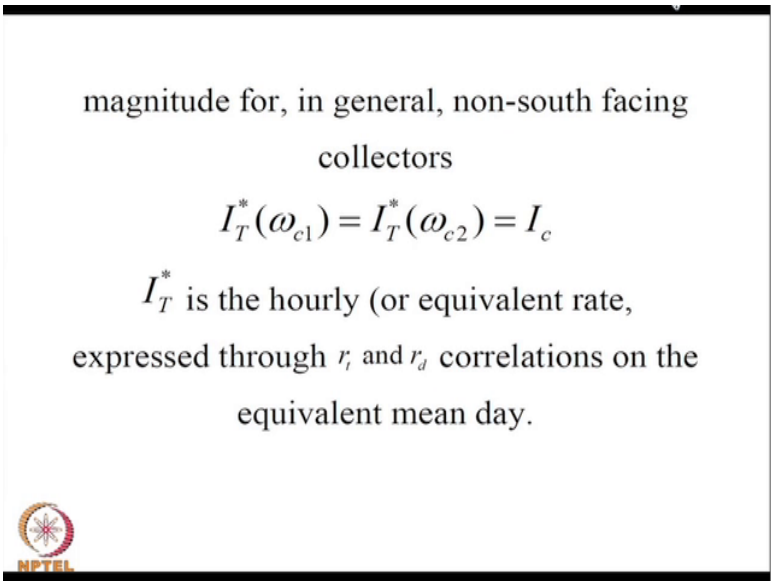

So, this can be analytically done when once you express I T star in terms of your r t and r d correlations.

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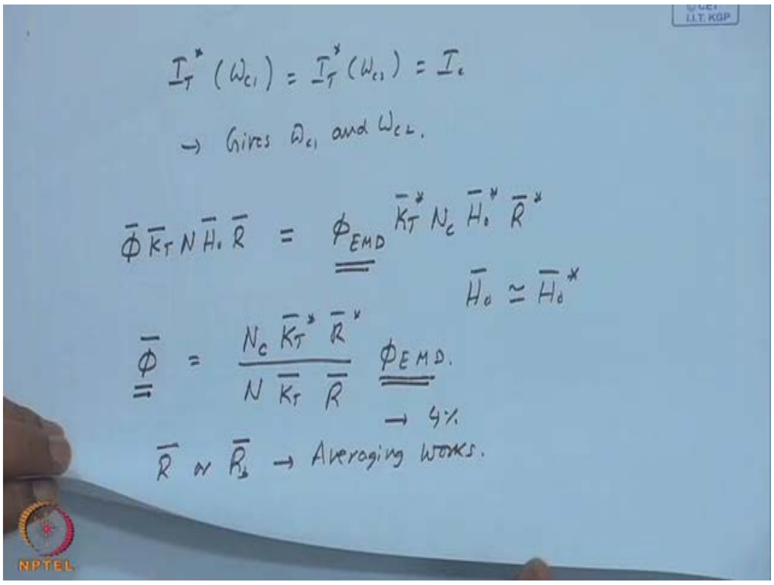

So, this I T star omega c 1 equal to I T star omega c 2 equal to I C. This gives omega c 1 and omega c 2. So, that can be expressed in terms of r t and r d correlations. There is no problem.

So, now if the monthly average daily utilizability with which we have been discussing all the time that multiplied by solar radiation falling on the collector surface, right. I have deliberately written in term of the non-dimension clearness index and analytically extra derivation radiation average multiplied by the number of days in the month multiplied by the average tilt factor R bar multiplied by the utilizability is nothing, but the solar radiation available above the critical level based on the monthly average daily utilizability. That should be the same as by simple energy balance phi EMD times K T bar star times N c, the number of days above the critical level times H rho bar star R bar star.

What we realize is the solar radiation available above the critical level, whether based upon the equivalent mean day of the average days with K T greater than KT minimum or all the days with the monthly average daily utilizability phi bar with corresponding N should be equal because the other days are always less than the critical level, and they do not contribute in the solar radiation falling on the collector surface above the critical level. So, from this you can solve phi bar is N c K T bar star R bar star upon N K T bar R bar into phi EMD.

Of course, I have approximated H 0 bar approximately equal to H 0 bar star because it is not necessary that these higher clearness index values are towards the end or towards the beginning of the month. They are randomly distributed. Still the affect to declination mean declination will be more or less, be the same as that of the entire area of the clearness indices. So, we can safely assume H 0 bar equal H 0 bar star even, otherwise it is not a big issue to calculate these things because it is analytically calculable quantity.

So, some substance is the monthly average daily utilizability has been related to utilizability of a single, and that single day being called the equivalent mean day. The properties of which are the clearness indices are always above the clearness index K T minimum and the average is K T bar star, so that the equation of I T minus I C being negative on any of these days does not arise. So, basically the (()) if you call from your R bar R b bar, there the averaging works mainly because when you are calculating the tilted solar radiation each day contributing.

So, taking a clue from that we have found out the days that contribute to the solar radiation above the critical level, and took the average of that and it predicts almost within 4 percent of route. That means Pereira compared to data or any other correlation that you can think of either the Klein's or Collares Perrier Robl, and this has got the advantage of it. It may be a long expression; it can be analytically expressed with one integration for set N 2 of the concentrating collector modes. It is not analytically integral, but nevertheless even making hour by hour calculation for one day is simple than going for all the 30 days.

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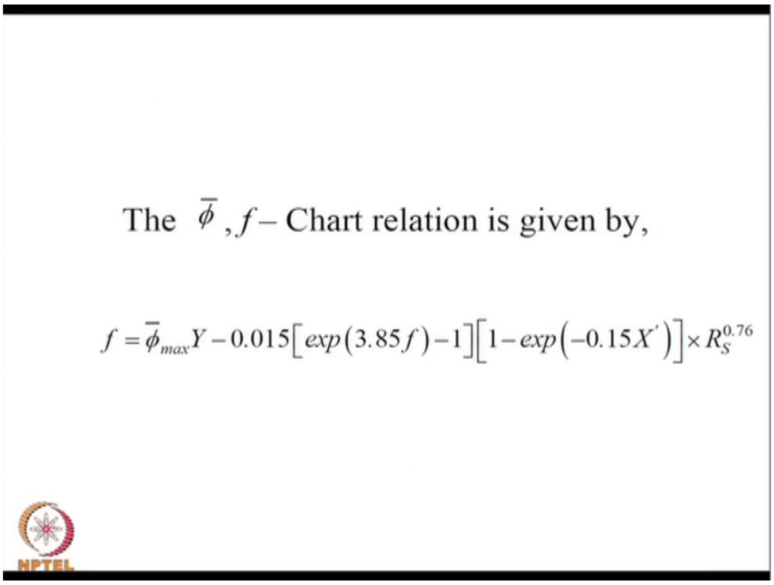

So, we have a fairly general method where will be the monthly average daily utilizability. The whole idea is assuming as this correlation is valid, rather the correlation may not be known from where that number phi bar max is coming. It may be from south facing surface or a non-south facing surface. So, if you have a method to calculate the monthly average daily utilizability for concentrating collectors or non-south facing flat plate collectors, perhaps the same correlation can be utilized using your phi bar max at the appropriate phi bar.

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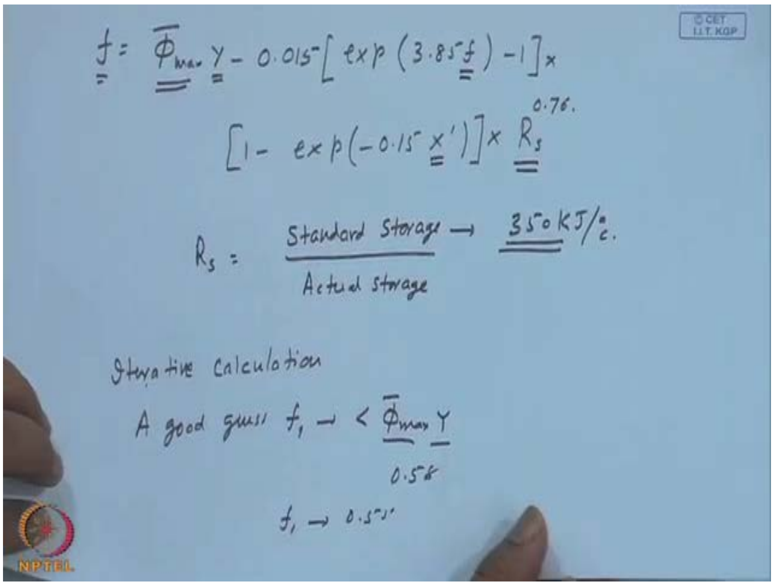

So, f is phi bar max y minus 0.015 exponential 3.85 f minus 1 times 1 minus exponential minus 0.15 x dash times R s to the power 0.76. We have done up to here and we try to describe how to include the tank losses also in brief in the last class, but my whole idea is the philosophy behind this phi bar of chart method is to relate the temperature at which delivery is desired to the minimum temperature, and a quantity called utilizability which indicates solar radiation available above the critical solar radiation available above a certain critical level.

This is the R s is the ratio of standard storage to actual storage 350 kilo joules per degree celcius. This roughly corresponds to 75 liters of water, 75 liters multiplied by the CP 4.18 comes about 350, but in phi bar of chart method instead of saying water or pebble bed etcetera, it is just given as the heat capacity value and all storage change can be taken care of. This is an implicit relation between f. So, it occurs on both sides, y is the same as the f chart variable, x dash is slightly modified, that is in terms of that 100 minus, T i is removed. That is only a 100.

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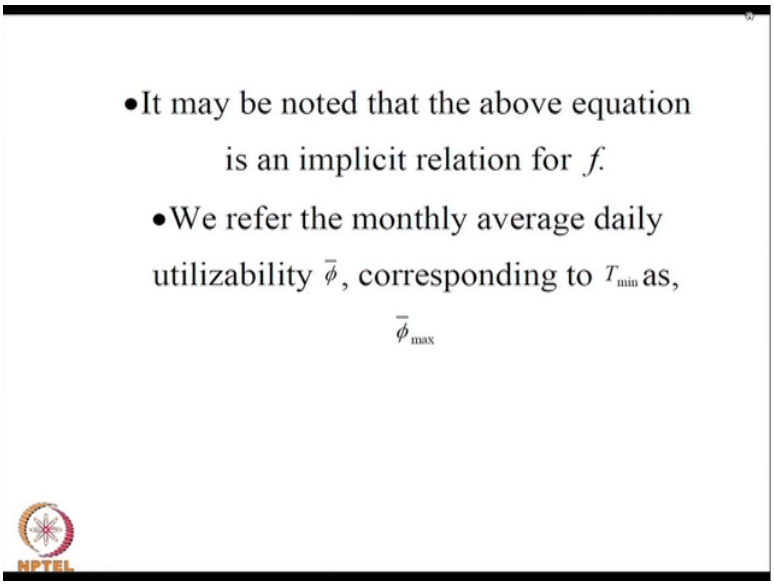

So, if you want this, require iterative calculation, a good guess first is slightly less than phi bar max y. This is calculable quantity. So, you know phi bar max. Let us say it is 0.58 and then I may guess f 1 as 0.5 phi. Then you can set up a Newton Grayson scheme or whatever, and you can easily interpolate or rather iterate in this relation to find actual solar load fraction met.

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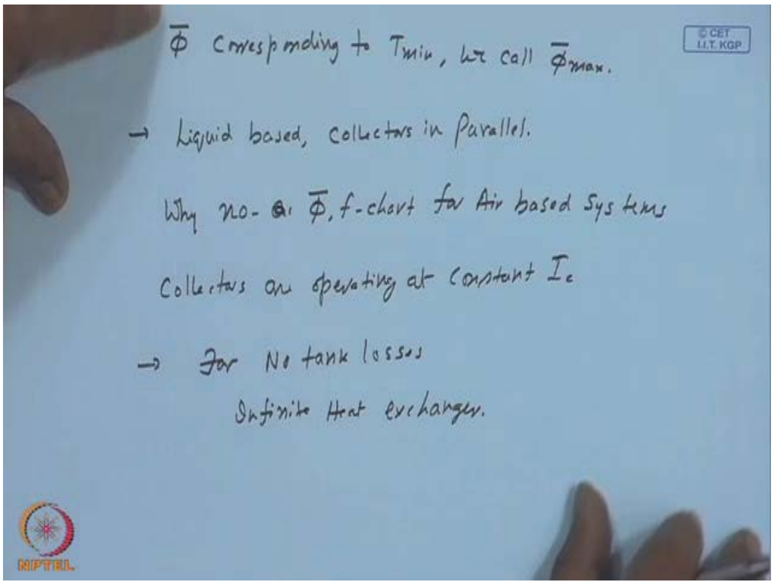

The only reason once again I emphasis the monthly average daily utilizability phi bar corresponding to T minimum we call phi bar max. That is all, nothing else. So, liquid based collectors in parallel, some of you may think of why no phi bar f chart for air base systems. So, this I could not really find out any reason, but then somebody can work if this is relevant for the application like drawing.

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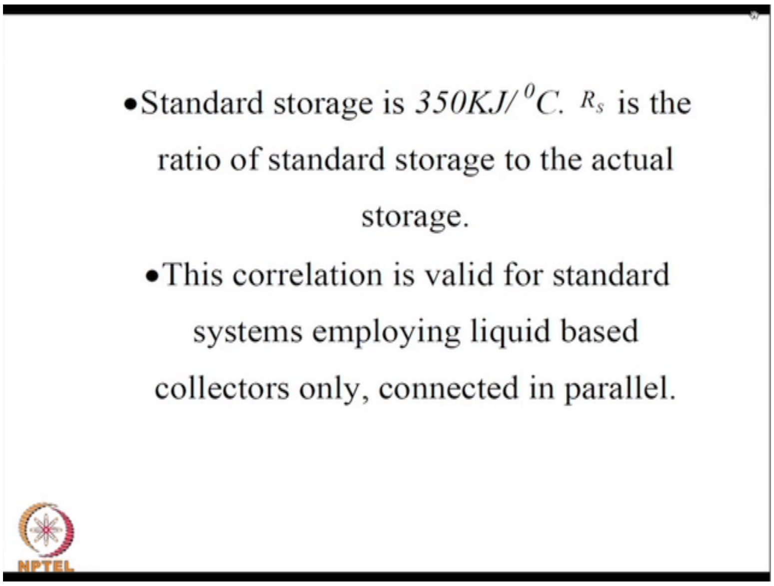

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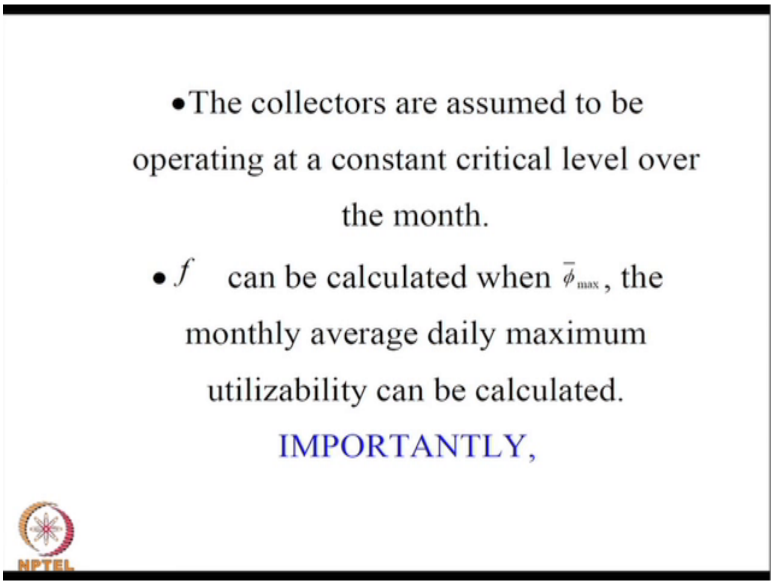

Let us say temperature of 50 degree is 60 degree celsius. Collectors are operating I T constant I C. All the average may be very much all right and as I had said that I C may be changed in from I c 1 to I c 2. Simply the ambient temperature average, let us say 15 degree celcius or you may have the minimum to 12, maximum to be 18. So, if you calculate the critical level between 12 and 18, there will be good variation. Consequently, utilizibility may be different on different days at least as far as the ambient temperature is concerned. However, the differences when average once again one may be underestimated, and other may be overestimated, consequently my phi bar max corresponding to T a bar may be an acceptable number, but somebody can verify these things.

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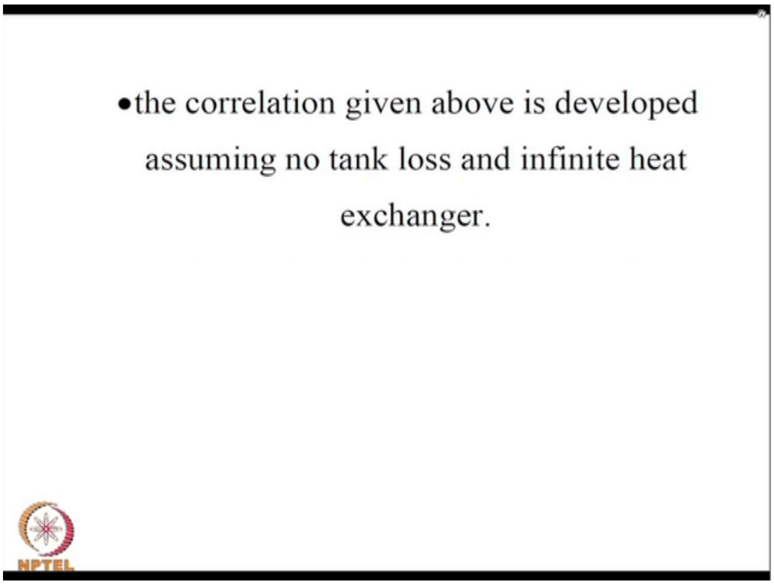

Importantly, this is for no tank losses and infinitely long infinite heat exchangers. So, this is I think got a little more emphasis and the previous lecture as well as this lecture, where we underplayed this aspect in the case of f chart method.

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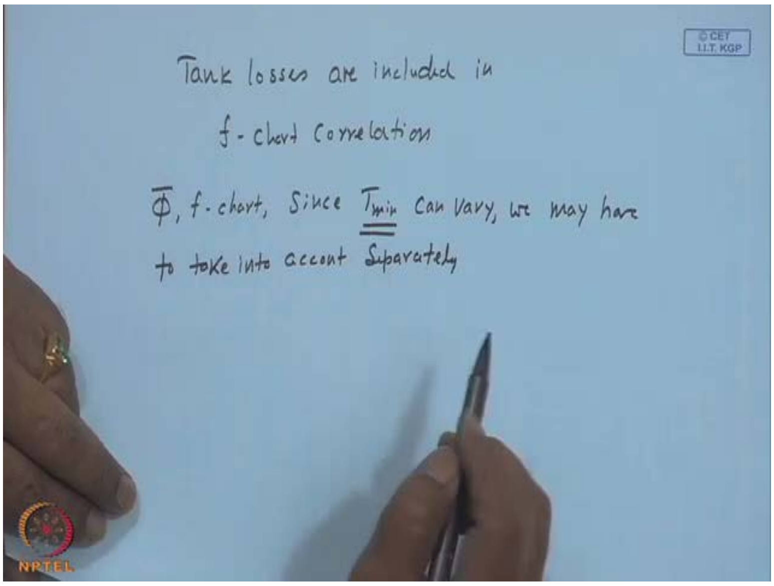

Tank losses are included in f chart correlation. In phi bar f chart, since I guess this is my logic, since T minimum can vary, we may have to take into account separately. In other words, f chart being applicable for another delivery above 20 c, one can expect some sort of uniform sort of proportionate losses whereas, the T minimum vary from 20 to 60 to 80. My tank losses could be quite significantly different. So, somebody has to do, I mean you may have to include separately. Similarly, heat exchanger also depending upon the temperature and the load condition, its effectiveness and its transfer capability may be varying.

So, once again we include heat exchanger, indeed in the f chart method also. Though, losses in the pipes and the tanks are not mentioned, heat exchanger size has been mentioned and if the heat exchanger size is not the standard size, you correct the variable y as y c by y is some exponential function, so that the heat exchanger is there and the f chart method also.

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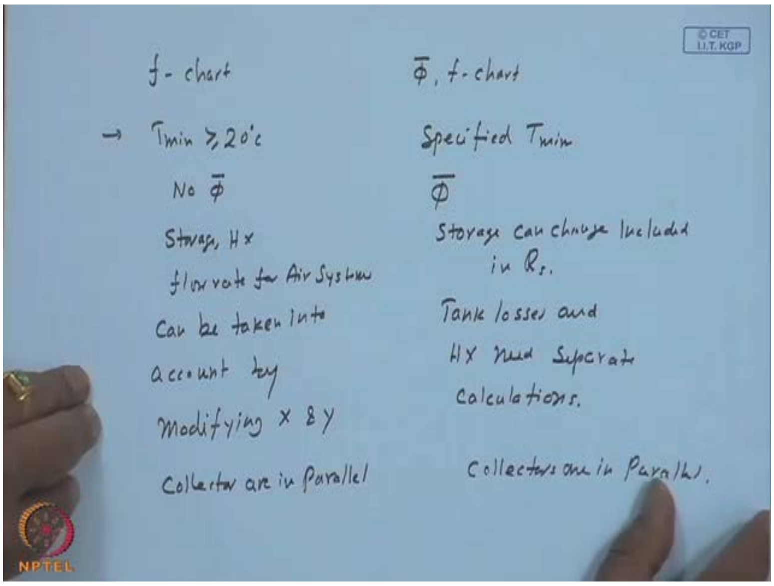

In final, what we need to see is f chart and phi bar f chart. This is T minimum 20 degree celcius here, specified T minimum. So, this has an additional parameter phi bar and this has no phi bar. Storage heat exchange flow rate for air systems can be taken into account by modifying x and y. Here, storage can change including in the factor R s tank losses and heat exchanger need separate calculations. In both the cases, collectors are in parallel here also.

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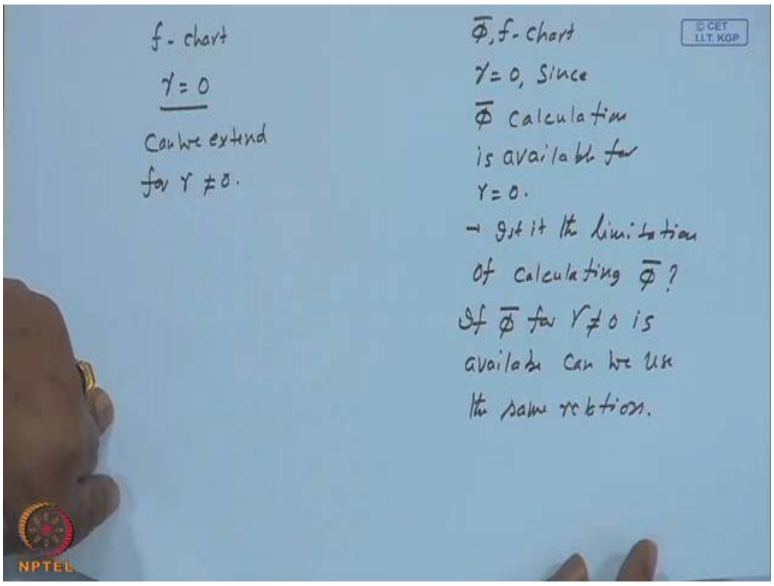

Again, f chart and your phi bar f chart, now gamma is equal to 0. Since, phi bar calculation is available for gamma is equal to 0. This can be extent for gamma not equal to 0. I just have to check up those parameters. You just see if gamma is not equal to 0 is included or not. I have given a table of conditions for beta phi etcetera. So, gamma I just do not recall exactly the 0 or set can be non-zero also. Here also, we need the limitation of calculating phi bar or if phi bar or gamma not equal to 0 is available can be used the same relation. Somebody may take up this problem, though if I remember, right Collares, Pereira and Robles.

So, I just said that replace this phi bar with for consonating collector or gamma not equal to 0 value or to use the same correlation. However, some verification needs to be done based upon the simulation results. Of course, the question also comes in because this has been developed few years back, nearly more than two decades back. So, competition power at that point of time is much higher, much less. Sorry, competition cost is much higher, competition power is limited. So, consequently, these design methods have had a good stake and now, if the competition power is lot of it is available and even cheaper. So, possibly one may go for simulation themselves instead of trying to find correlations. Nevertheless, all the utility of the simplified methods particularly in applying in the industry is always necessary and it is good.

So, what we need to do, what we shall do in the next lecture is find a method and methodology to calculate, include the tank losses and the heat exchanger effect and see how the solar load fraction in the phi bar of chart varies. So, in a nutshell, this is just the solar load fraction has been correlated to two parameters, x and y. In the case of f chart, where x is the non-dimensional collector loss and y is a non-dimensional epsilon energy.

Similarly, in the case of phi bar f chart f has been related to similar variable x dash and y and initial variable is the monthly average daily utilizability which combines the operating temperature, and the solar radiation statistics. This relation is an implicit relation yet to include tank losses and heat exchanger.

Thank you.