Solar Energy Technology
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Lecture - 35
Exercise – 2

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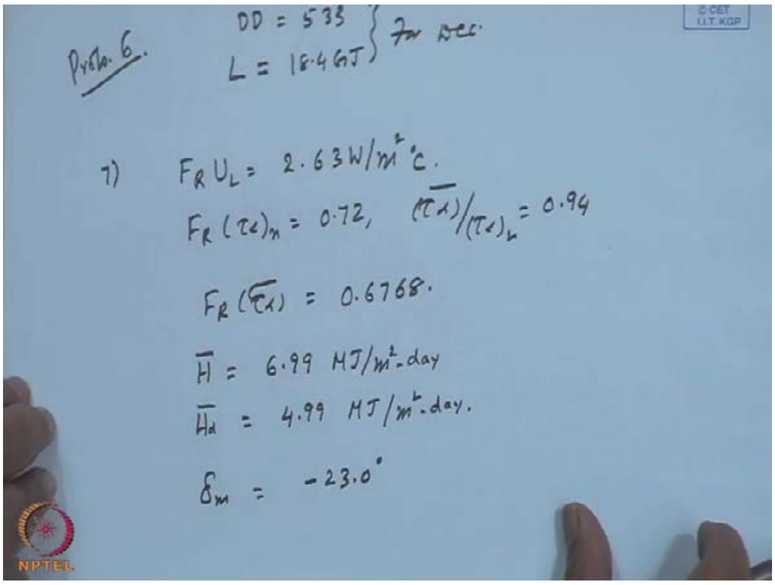

Last time, we were trying to design a space heating system in Srinagar and the space heating load has been calculated as in problem number 6, 18.4 gigajoules in a month and the degree days we have calculated for the month of December as 533, for December. This is from problem 6. So, 7 the collector properties are F R U L is 2.63 watts per meter square degree c, F R tau alpha normal is 0.72 with tau alpha bar upon tau alpha n 0.94 calculated by the detailed method, we have described in the earlier problem while dealing with the phi bar of chart method. So that F R tau alpha bar will be the product of these two equal to 0.6768. Then the data is monthly average daily radiation is 6.99 mega joules per meter square day and the diffuse radiation is 4.99. So, you can understand it is a cloudy day and the mean declaration for the month of December is minus 23.0 degrees.

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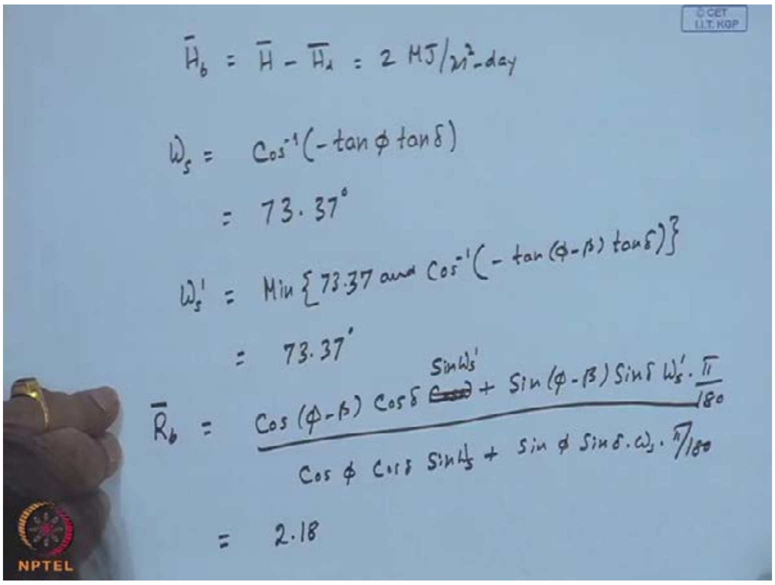

So, with this or you have got the direct radiation H b bar has H bar minus H d bar equal to 2 mega joules per meter square day. So, first our task will be to compute the solar radiation received by the surface. And for that I need the sun set hour angle omega s is cos inverse minus tan phi tan delta which is we calculated 73.37 degrees. And omega s dashed for the tilted surface is the minimum of 73.37 and cosine inverse minus tan phi minus beta tan delta. We have the trigonometric argument; when delta is negative this minimum will turn out to be 73.37 in the northern hemisphere.

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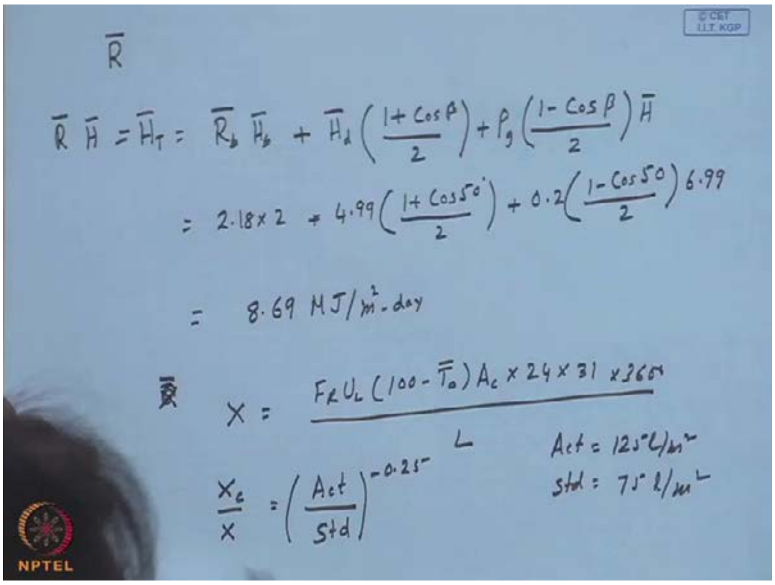

Now, the tilt factor for beam radiation R b bar is the familiar formula cos phi minus beta cos delta cos omega plus R b bar sorry, this should be sine omega s dashed plus sine phi minus beta sine delta omega s dashed into pi by 180 upon the cos theta z, that is the zenith angle cos phi cos delta sine omega s plus sine phi sine delta into omega s into phi by 180 which turns out to be 2.18. So, R b bar for this situation is 2.18. And your R bar for the entire variation, if you have H t bar equal to, we actually do not need this except later on we may, R b bar H b bar, which is R bar H bar for the sake of completeness plus H d bar times 1 plus cos theta by 2.

You recall all the formula we derived earlier r being used in this few examples that we are doing as application of phi bar f chart method or the f chart method. So, this will be a 2.18 into 2 mega joules plus 4.99 into 1 plus cos 50 degrees that is the beta by 2 plus 0.2 into 1minus cos 50 by 2 into 6.99, that turns out to be 8.69 mega joules per meter square day. This is the solar radiation falling on the collector surface in the month of December, the average daily value. Now, the f chart variable X is the non dimensional collector loss. X is F R U L times 100 minus ambient temperature average multiplied by A c into number of seconds in the month by the load on the system. And since the storage is conceded to be different you have got X c by X is actual by standard to the power minus 0.25.

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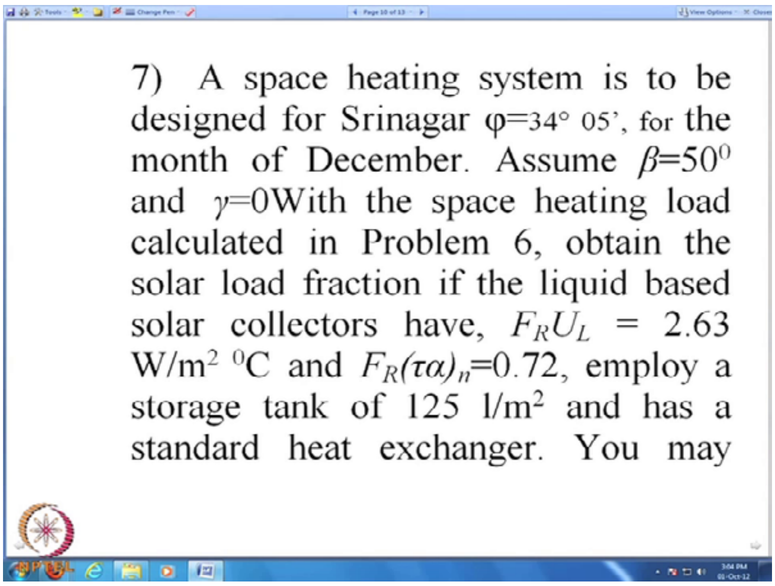

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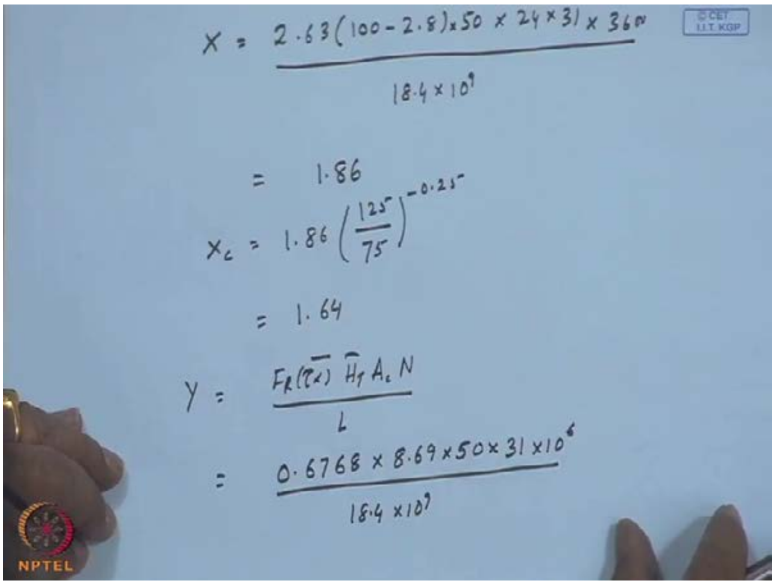

I will, let me just check up. Heat tank is 125 liters per meter square, actual storage is 125 liters per meter square compare to standard of 75 liters per meter square. So, we need to correct the variable X as we have done here. So, first X will be 2.63 into 100 minus 2.8, which we have calculated while calculating the degree days, the average temperature times 50 times 24 into 31 into 3600 by 18.4 into 10 to the power 9 joules, this will be 1.86. So, X c will be 1.86 times 125 by 75 to the power minus 0.25, which will be equal to 1.64. So, larger storage leads to a smaller X c, which basically means a lesser loss and a hence higher solar load fraction, which can be easily understood because we have got a larger storage so there will be more storage.

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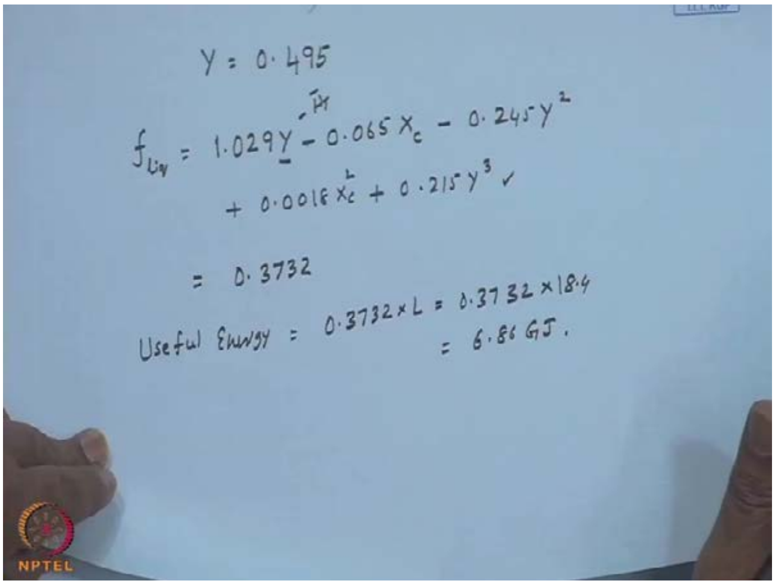

So, Y is F R tau alpha bar times H t bar A c into number days in a month by the load which will be equal to 0.6768 times H t bar is 8.69 mega joules multiplied by 50 times 31 into 10 to the power 6 that make it joules by 18.4 into 10 to the power 9 that makes the load also in joules, which gives you Y as 0.495. So, I use the correlation for the liquid based f chart; 1.029 Y minus 0.065 X. Now, I will right directly write the X c because I have already corrected minus 0.245 Y square plus 0.0018 X c square plus 0.215 Y cube.

So, this comes to be 0.3732. So, useful energy delivered by the solar energy system to meet the load will be the solar load fraction times L that will be 0.3732 times 18.4 that will be equal to 6.86 gigajoules. So, this the f chart method only variation is that we said that the standard storage in 75 liters instead of that we have actual storage of 1. 125 liters per meter square of the collector area. So, the variable X has been corrected accordingly. And we applied the f chart correlation that require the calculation of Y which required basically H t bar out of the ones to become computed, rest of them are more or less known to us. So, you have got 6.86 of the kilo joules met out of the 18.4 gigajoules by the system half square meters 50 square meters.

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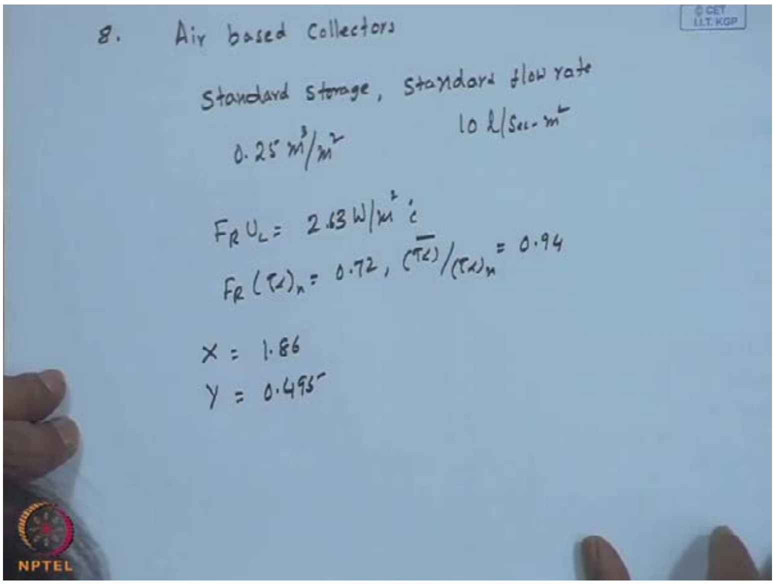

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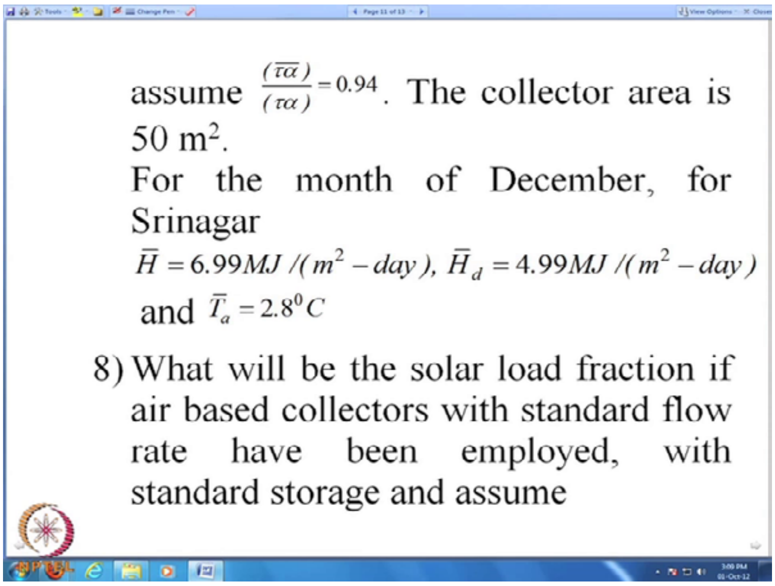

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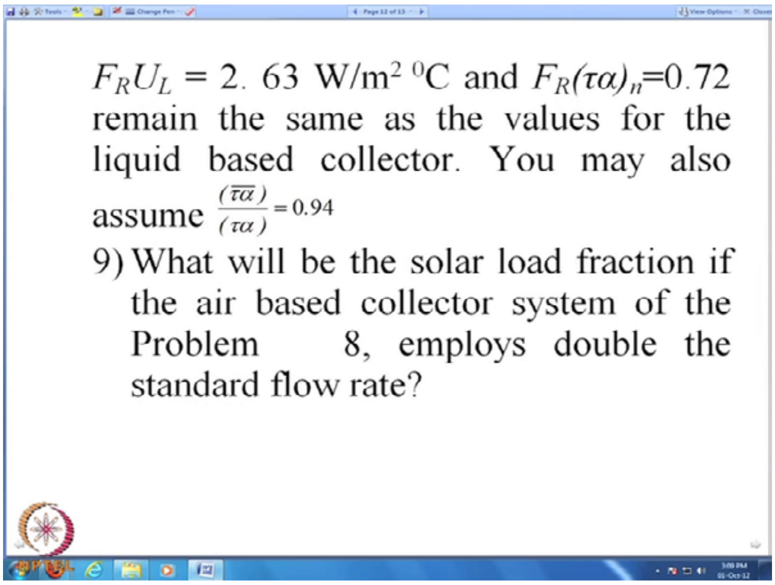

Now, problem 8 is a slight variation. If standard flow rate and standard storage has been employed for the same F R U L and F R tau alpha bar as calculated and what will be f, let me just check up. What will be the solar load fraction if air based collectors with standard flow rate have been employed with standard storage and assume F R U L is equal to so much and F R tau alpha n. So, second one is if I use air based collector and standard storage, what is this standard storage; a 0.25 meter cube per meter square of the pebbles and then standard flow rate, what is the standard flow rate; 10 liters per second per meter square under N T P. So, these are the numbers I am repeating, so that you will be remembering and when once you say the standard storage and standard flow rate you must almost be able to know what they are.

X and Y do not change of course, it is also given F R U L is same 2.63 watts per meter square degree c, F R tau alpha normal is 0.72 and tau alpha bar by tau alpha normal is 0.94 and which were then X is 1.86, the pervious number uncorrected because these are standard storage and standard flow rates, Y is equal to 0.495. So, this is only just to show if an air based system with collector parameters being similar value same values as 2.63 and 0.72 are equal to that of liquid system, what will be the difference in the solar load fraction. That in a way explain this superiority or otherwise of your air based system verses the liquid based system in addition to other advantages or disadvantages like pumping power being higher for a air base system etcetera.

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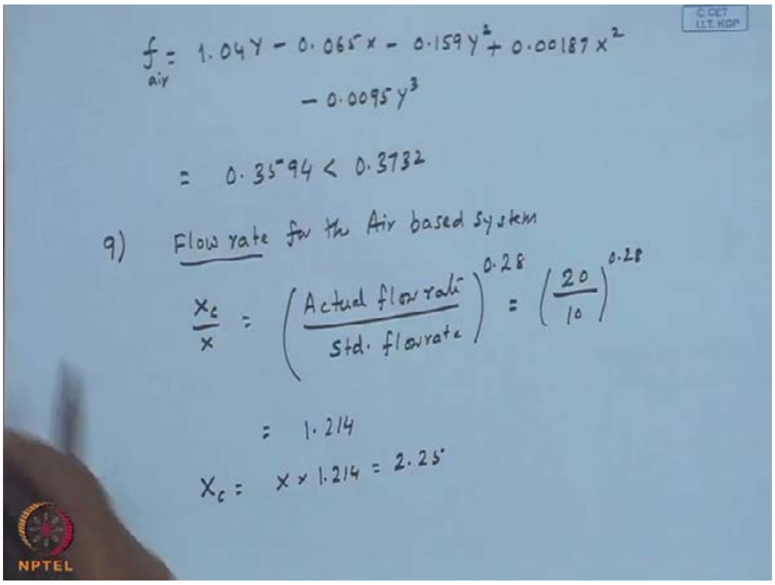

So, f is a slightly different expression. So, I will write it as f air so that u will know that this is for the air based system minus 0.065 X minus 0.159 Y square plus 0.naught naught 187 X square, just there are differences in the sign compare it to the liquid based system that you can note the numbers are more less comparable. The major difference to be tackled or understood is the whether a equivalent cost air based electrical will have same F R U L and F R tau alpha as that are the liquid based collector. So, in general they are little poorer, but given that they are the same, now we will come out with this f air with this values of 0.495 for Y and 1.86 for X. This will be 0.3594 which is less than the previous value, which is 0.3732.

So, air system does slightly inferior to the performance of the liquid based system. That is generally attributed as due to or rather insufficient stratification or less stratification in the storage medium than what it will be for the air or the leakages will be little more, the heat losses may be little more consequently. Hence, the load fraction made by the air system for comparable F R U L and F R tau alpha normal in general is lower than that of for the liquid system. Now, let us see if you can improve the heat transfer, flow rate is double for the air based system. You may recall for the liquid based system the corrections or for the heat exchanger not being epsilon l c min by u a h equal to 2 and the other one is for the storage.

For the air based system the corrections for the storage and the flow rate because the performance is the highly depend upon the flow rate for air based systems. So, the correction is now X c by X equal to actual flow rate by standard flow rate to the power 0.28. So, this will be standard flow rate is 10, so actual flow rate is 20 to the power 0.28, that will be equal to 1.214. So, the corrected value of X c will be X into 1.214 which will be 2.25. So, this is little unexpected, I will tell you why it is unexpected and then also I will tell you why it should be expected.

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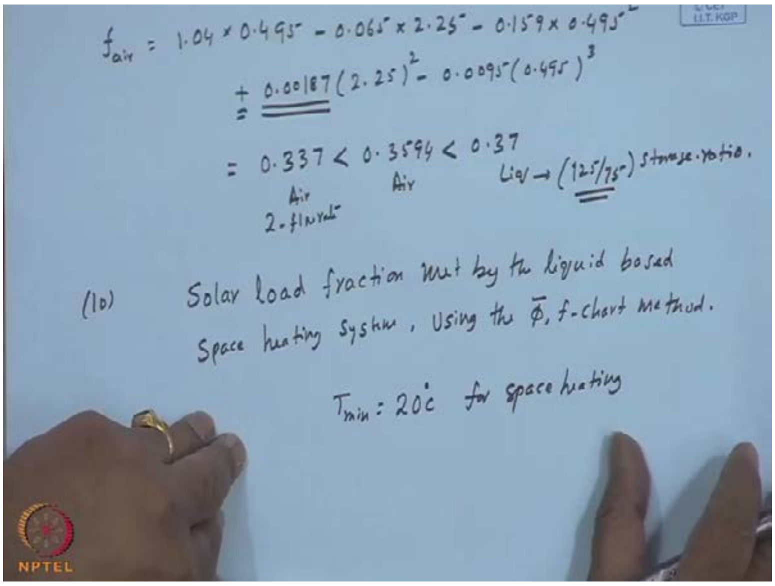

So, f is air again 1.04 into Y remains the same 0.495 minus 0.065 times X is 2.2 let me check 2 5 correct 2.25 minus 0.159 into 0.495 square plus 0.00187 times 2.25 whole square minus 0.0095 times 0.495 whole cube. This turns out to be surprisingly 0.337 less than your previously value 0.3594. So, this actually is attributed due to this term with a plus sign and X c has increased when the flow rate is doubled to that of the standard flow rate. One reason could be people attribute that at higher flow rate the storage is very much disturbed, so stratification is not maintained. Consequently, the effective temperature goes down making the effective solar load fraction lower than what it would be at this standard flow rate.

So, standard flow rate is sort of a (( )) flow rate also. So, consequently you have the you can say and this is less than 0.37 or whatever it is liquid, air, air at 2 times flow rate. Of course, this liquid is at 125 by 75 storage ratio. So, this is at a higher storage. So, if you bring down the storage of this it may be comparable this is 3 6 and 3 7 and there might not be much difference between these two, that is what we should not forgot. Let us not say in general air system is poorer, no here this got the benefits because your storage is higher than the standard storage whereas, here this is the standard flow and rate standard storage. This depreciation in the performance is because of the flow rate being higher and that has got its own characteristics as far as air based system is concerned.

And lastly, this is problem number 10 which should bring us close to this exercise on f chart and phi bar f chart. So, calculate the solar load fraction met by the liquid based obviously space heating system (( )) problem 7 or 8 etcetera using the phi bar comma f chart method. Now, this is surprising thing, what I have in my mind. Phi bar of chart is general irrespective of the system details. T minimum can be specified, I may have a load heating stranger etcetera, but if I use the phi bar chart method and consider T minimum equal to 20 degree c for space heating, how will this perform? So, the calculation is little more involved then the f chart method, but nevertheless the generality of the phi bar f chart method or otherwise can be established.

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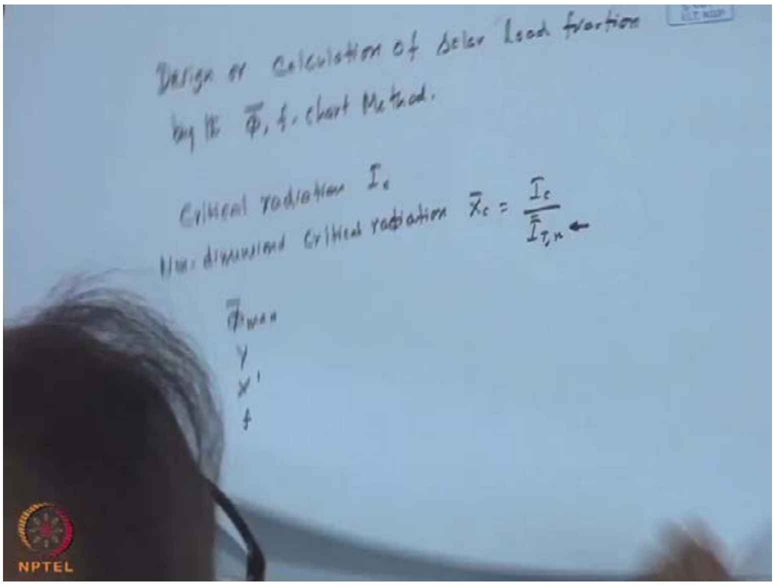

So, we have gone through the steps in a problem 6 or 5 whatever, where we were using the phi bar chart method for calculating the process heating system. So, exactly the same sequence of calculations will be done. So, I would now say design or calculation of solar load fractions by the phi bar comma f chart method. So, I need the non dimensional critical level first of all for which I need the critical. Let me put it down critical radiation level I c and non dimensional critical radiation radiation X c bar equal to I c by I t at noon on the average day of the month and then phi bar max Y X dash and then f.

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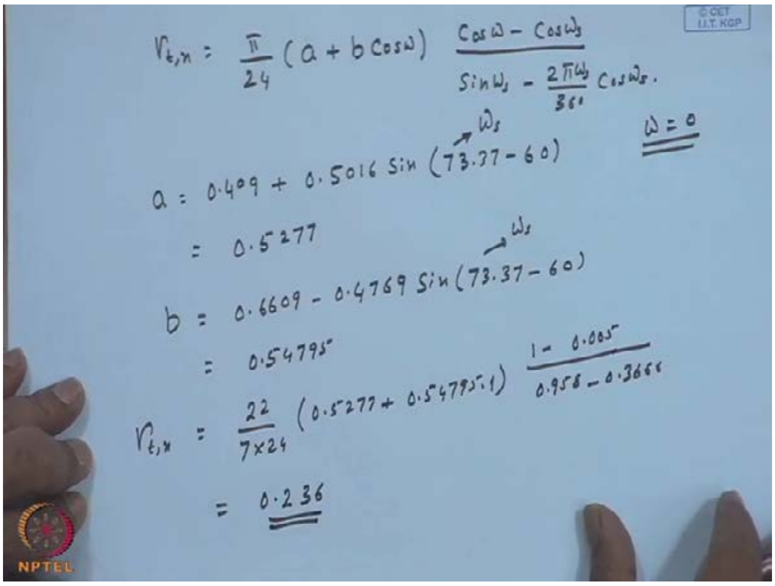

So, this is the sequence in which we proceed, sort of with the first chartable quantity is this I t noon for which we need r t n equal to pi by 24 into a plus b cos omega times cos omega minus cos omega s upon sine omega s minus 2 pi omega s by 360 times cos omega s, where a is equal to 0.409 plus 0.5016 sine 73.37 minus 60. Remember that this is omega s which we have already calculated; this comes to 0.5277 then b the constant as a 6609 minus 0.4769 sine 73.37 minus 60 same omega s over here, which will be equal to 0.54795. So, you have got r t n is 22 by 7 into 24 times 5277 plus b is 0.54795 into cos omega; omega is 0 omega because it is a noon time into 1 to be explicit times again 1 minus 0.o o 5, omega s is 73 pretty large, cos omega close to pi by 2 I mean, by 0.958 sine omega s it will be close to 1, minus 0.3666.

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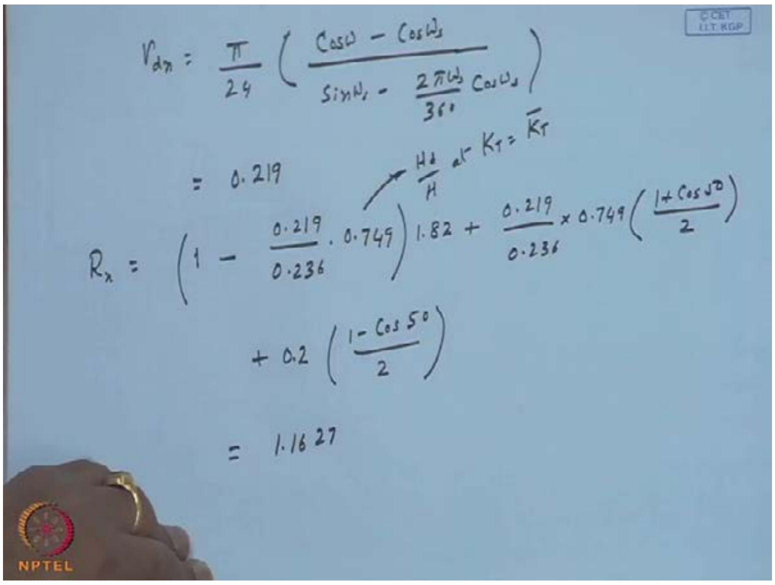

So, this will turn out to be 0.236, then r d n is pi by 24 times cos omega minus cos omega s by sine omega s minus 2 pi omega s by 360 cos omega s. So, that a plus b cos omega you can easily subtract, that is the advantage of some intermediate calculations though I have not shown just divide by that number you will get 219. So, we got r t n and r d n. Now, R n that is noon time (( )) 1 minus r d n by r t n times R n 0.749 H d by H n I am sorry, times 1.82 plus 0.219 by 0.236 into 0.749 into 1 plus cos 50 by 2 plus 0.2 times 1 minus cos 50 by 2. Let me finish, I will explain I am sure you have doubt, 1.1627.

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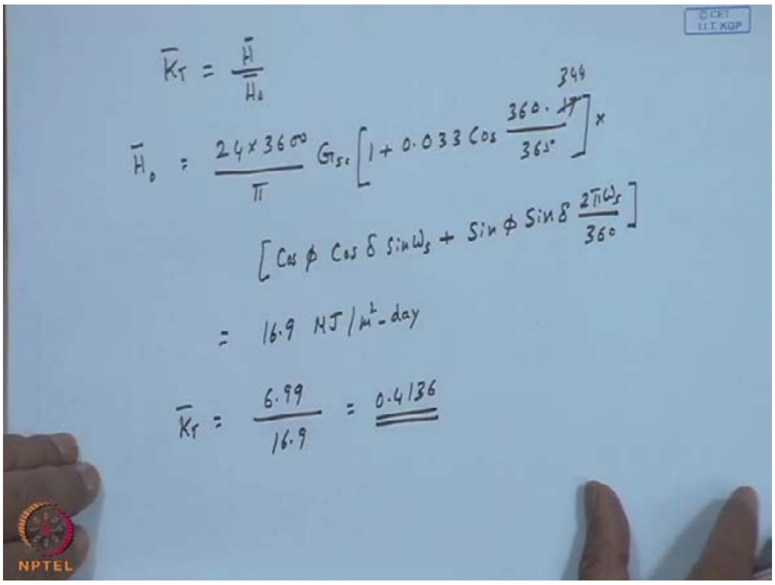

This is H d by H at K t equal to numerically K t bar. So, this calculation I will show you now. So, r n is 1.1627, but this is where I mean the number of calculation increase. K t bar is H by H 0 bar, H bar is known to us 6.69. H 0 bar is 24 times 3600 by pi G s c times 1 plus 0.033 cos 360 times n is 17 by 365 multiplied by cos phi is 284 minus or 344 cos phi cos delta sine omega s plus sine phi sine delta 2 phi omega s by 360. I think this should be 344 just check up, I have made the calculation correctly, but here writing is wrong. 2 pi omega s by 360 because this should be the midpoint of the month of December, 2 pi omega s by 360.

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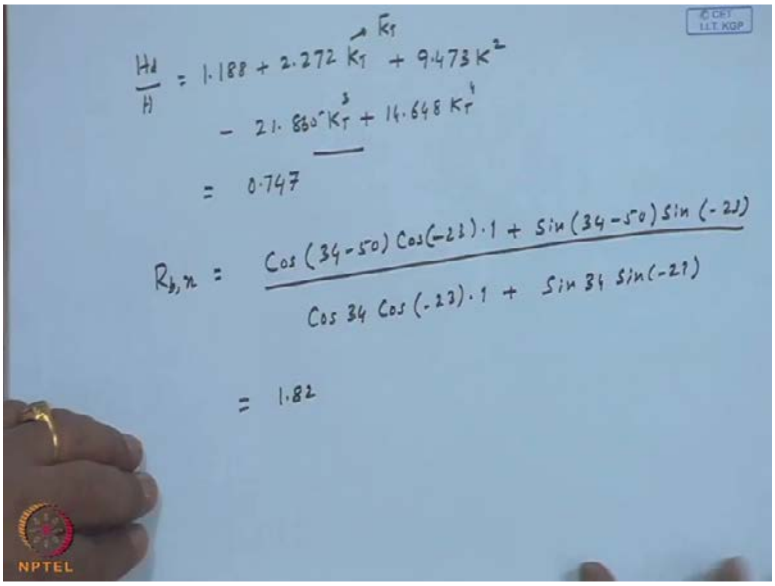

So, this will turn out to be 16.9 mega joules per meter square day or you can look up at the charts in text book with latitude of 35 degrees approximately, it will turn out to be correct. And your K t bar is 6.99 by 16.9 which will be 0.4136, as expected this is a low value. So, now H d by H equal to 1.188 plus 2.272 K t which will be equal to numerical K t bar plus 9.473 K t square minus 21.865 K t cube plus 14.648 K t to the power 4 or this comes out to be 0.747. These things I am writing again because if I just say H d by H is equal to 0.747 you may not be knowing which relation I have picked up.

So, this is at the expense of little repetition, but then I suppose it is for the clarification and you will by the end of the course you should remember looking at their relation. This is not given to you, this is given to you, you should be able to say this is H d by H. Now, we also require R b at the noon time, this will be equal to cos phi minus beta, this we have done in enough times, times cos delta into cos omega which is 1 plus sine 34 minus 50 times sin minus 23 by cos phi cos delta cos omega plus sine phi sine delta. So, this comes out to be 1.82, these were the things that we have used in calculating R n.

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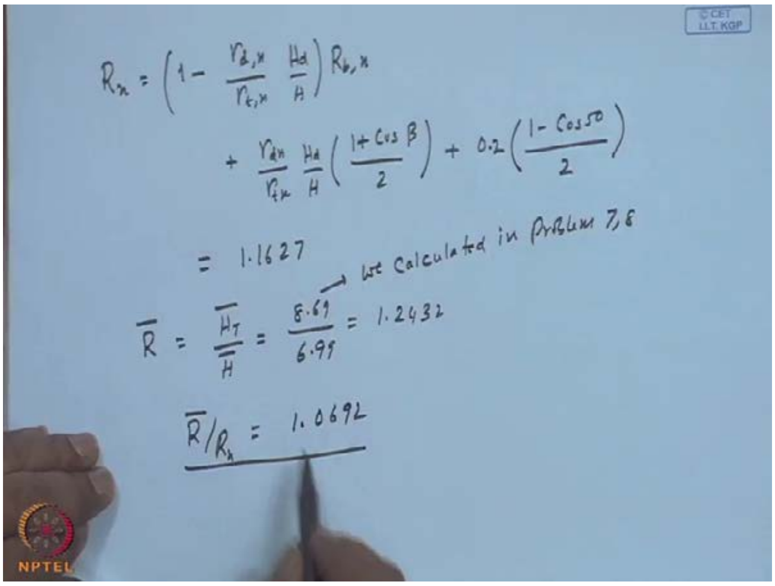

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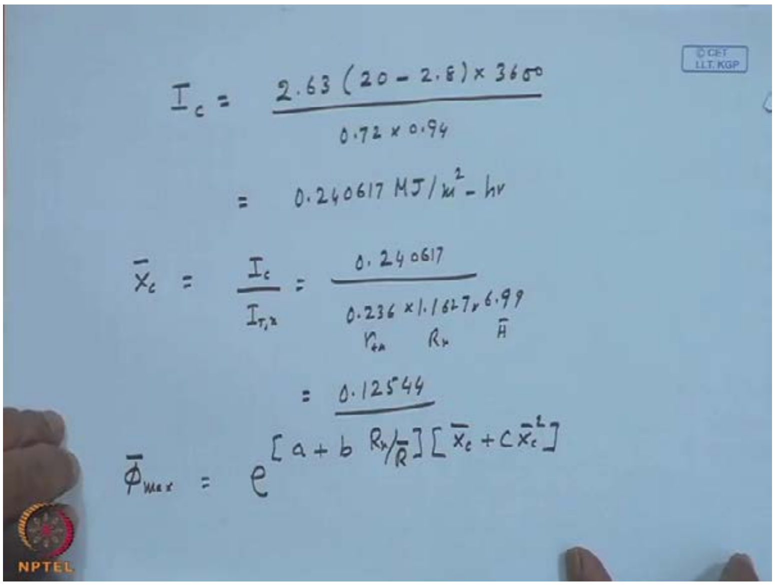

If in the formula 1 minus r d n by r t n times H d by H times R b noon plus r d n by r t n H d by H or times 1 plus cos beta by 2 plus 0.2 times 1 minus cos 50 by 2. This comes to 1.1627 and your R bar is H t bar by H bar equal to 8.69 by 6.99 equal to 1.2432. So, remember this we calculated in problem number 7 seven or 8. Now, R bar by R n the ratio required in calculating the monthly average daily utilizability turns to be 1.0692. So, we calculated one of the things required, then we will go ahead with I c critical radiation level 2.63 F R U L into T minimum is now 20 minus T ambient is 2.8 times 3600 the time factor not be forgotten by 0.72 into 0.94.

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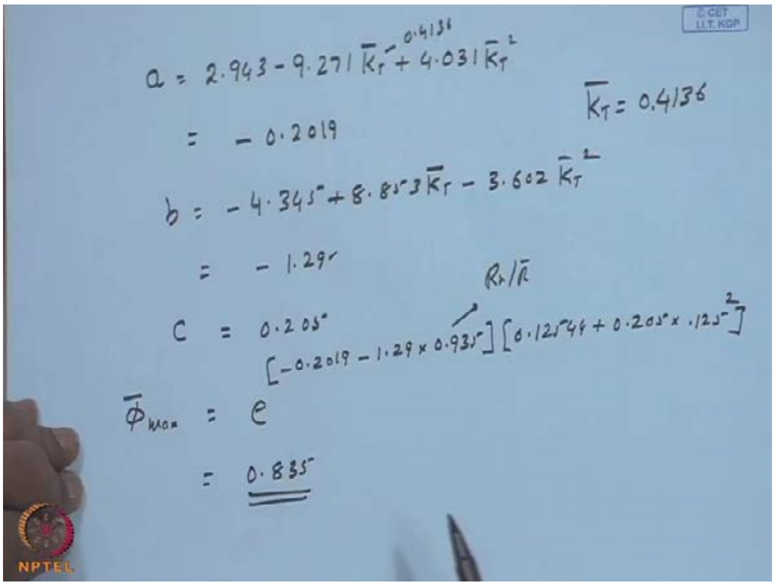

So, this will be equal to 0.240617 mega joules per meter squared hour. The non dimensional critical level will be I c by I t n which will be 0.240617 by r t n R n into H bar, r t n, R n, H bar. This is a mega joules this is also an mega joules, no problem, this equal to 0.12544. So, this is another thing that we require in the phi bar f chart method. Now, phi bar max will be exponential to the power a plus b times R n by R bar times X c bar plus C X c bar square. So, a, the constants are 2.943 minus 9.271 K t bar plus 4.031 K t bar square. So, this will be K t bar square 0.41 something which we already K t equal to K t bar somewhere we have written 0.4136, I can write it here.

So, this is minus 0.2019, b is minus 4.345 plus 8.853 K t bar minus 3.602 K t bar square, this will be equal to minus 1.29. Then c you can calculate it over turn is the formula that turn out to be 0.205. So, phi bar max e to the power minus 0.2019 minus 1.29 that is this into R R n by R bar, which will be 0.935. This is R n by R bar which is 1 by R bar by R n, which we have calculated earlier times c point sorry, X c bar 12544 plus 0.205 into 0.125 square. So, this will be 0.835. So, the utilizability is pretty high. The reason is its operating at a T minimum of 20 degrees considerably lower than for the process heating system that we were using earlier, which is was at 60 c.

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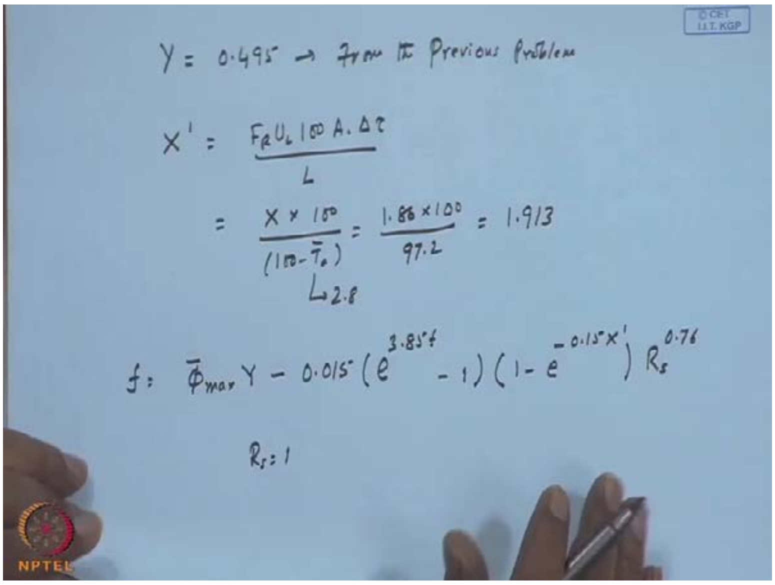

And particularly, there are logic to say that non dimensional utilizability phi bar will be higher at lower K t bar. This is not to imply that there is a solar radiation received is higher at a lower K t or any such thing. The non dimensional value of phi bar is higher at a lower case K t bar, that is come from the non uniformity of the (( )) index or the non uniformity of the solar energy, more non uniformity if K t bar is lower. Now, I need Y equal to 0.495 from the previous problem. And now I need X dashed, you can write of course, as F R U L into 100 into A c into delta tau by L which will turn out to be R power previous X multiplied by 100 because that is this 100 by 100 minus T a bar because X contains 100 minus T a bar.

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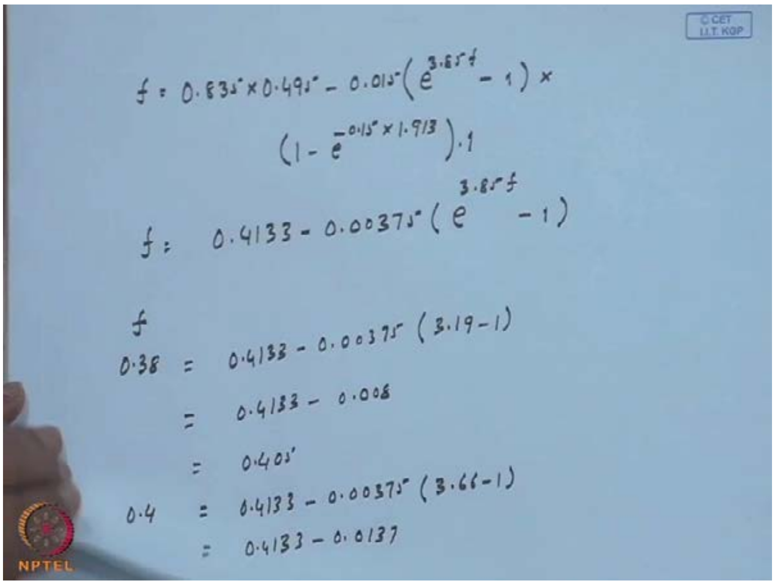

So, simpler way since we already made calculation, 1.86 into 100 by 97.2, this is 2.8. So, this will be 1.913. Now, we got Y, we got X dashed so we are all set to calculate the solar load fraction. f is equal to phi bar max Y minus 0.015 e to the power 3.85 f minus 1 multiplied by 1 minus e to the power minus 15 X dashed times R s to the power 0.76. So, standard storage R s is equal to 1 and first we have calculating no heat exchanger, no tank losses. So, f will be phi bar max is 0.835 times Y 0.495 minus 0.naught 15 into implicit e to the power 3.85 f minus 1 multiplied by 1 minus e to the power minus 0.15 X dashed into 1.913, X dashed is 1.913, that is correct times 1, that is the standard storage to the actual storage ratio.

So, this f will be 0.4133 minus 0.00375 times e to the power 3.85 f minus 1. So, this will be, that is right. We will start with a guess of f, let us take it as 0.38 because we calculated by f chart if it is to be close it could be 0.438 and should be less than 0.4133 so it just I will chose some value like 0.38. That is equal to 0.4133 minus 0.00375 times this is a you put a that 3.85 into 0.38 that will turn out to be 3.19 minus 1 which will be 2.19 equal to 0.4133 minus 0.008, that is 0.405. So, this is close, but not as good as it can be, we can simply somewhere it should be lying in between these two values because if increase this it will decrease, but at the same time if I increase equal to 405 the number would be less than that.

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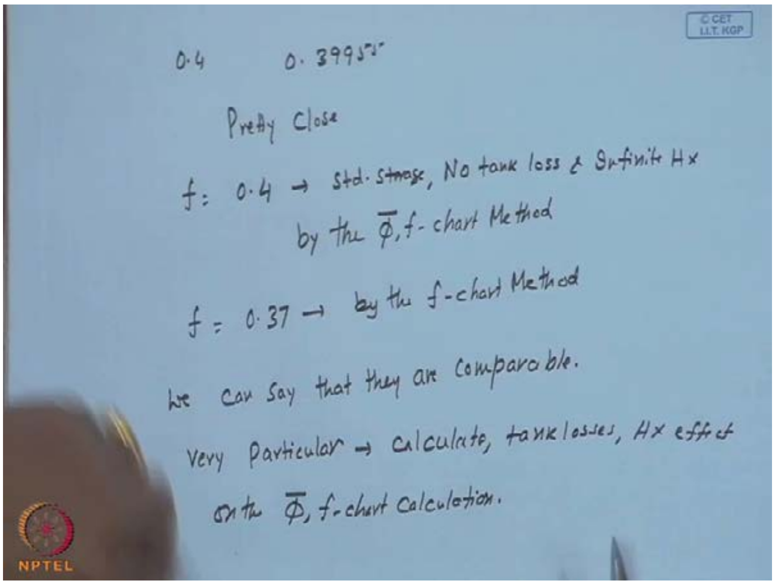

So, I will choose next guess will 0.4, that will give me phi bar max Y 0.49 that is 0.4133 minus 0.00375 times this is 3.66 minus 1, which is 0.4133 minus 0.0137. So, left hand side will be 0.4 and the right hand side will be 0.39955, pretty close. So, you got f of 0.4 for standard storage, no tank loss and infinite heat exchanger by the phi bar f chart method. For the same space heating system this is about 0.37 by the f chart method. Even these values we might say can say that they are comparable and if we want to be very particular or calculate tank losses and H x effect on the phi bar f chart calculation.

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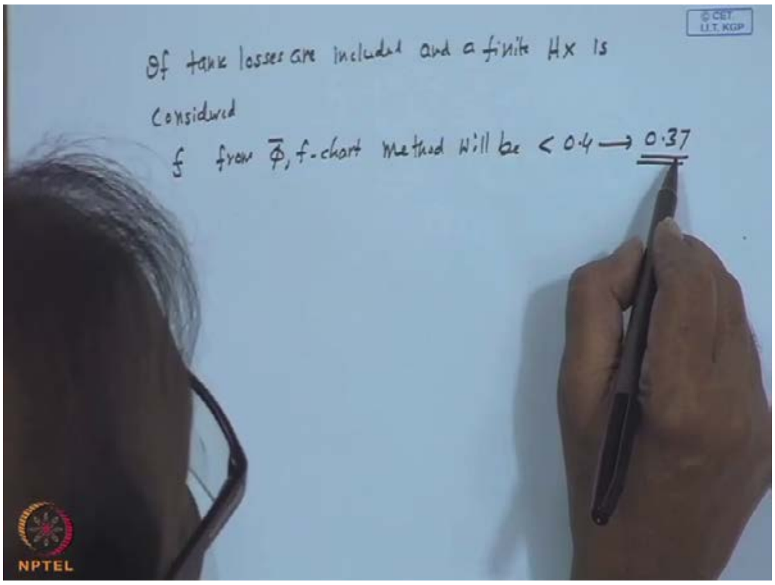

So, obviously if tank losses are included and a finite heat exchanger is considered, f from phi bar f chart method will be less than 0.4 goes close to 0.37. Of course, 0.37 also slightly inflated because the storage is higher, we can do the same thing for the f chart method also. So, these values are quite comparable. So, about 10 examples we have solved or to illustrate the calculation for the phi bar of chart method to obtain solar load fraction, then how to include the tank losses, then subsequently include the effect of the heat exchanger, then we considered a equivalent space heating system of our the Indian location of Srinagar obtained by an approximate method, the degree days which coincided with the actual calculation, the reason being no time the temperature is higher than the minimum comfort temperature of 20 c or 19 c, consequently this calculation helps, is accurate.

And then we use the f chart, both air based as well as liquid based to calculate the solar load fraction and studied the effect of the non standard storage and non standard flow rate for air collectors. And we found that the performance in general is comparable, however the air based system performed slightly inferior to that of the liquid based systems and in addition to higher pumping or power requirement. Subsequently, we took a exercise, how would the phi bar f chart method be to design the space heating system or to calculate solar load fraction for spacing setting system. So, apart from the intricate details, differences in the details of the system configuration you have a T minimum requirement for 20 degree c in the case of space heating system.

So, I shall use the phi bar f chart method giving assigning T minimum to be 20 c. We carried out that exercises calculating the corresponding critical level, corresponding non dimensional critical level and the monthly average daily utilizability and through a nitrative process to solar load fraction which came out to be 0.4 compare to 0.37 for air based system and this 0.4 is without considering the tank loses and assuming an infinite heat exchanger. Consequently, if these losses are included and heat exchanger effect is taken to account phi bar f chart at least for the example we have considered are very close.

And with experience I can tell you I made quite a few such calculations. One can be interchangeably used in other words phi bar f chart can be used for the liquid based f chart for space heating domestic hot water, but the not the other way round, you cannot get the process heating results from the f chart method. And of course, the equivalence of an air based system by phi bar f chart method is not available. This is the some substance of the design method, which you have to make 12 monthly calculations. However, even for yearly predictions by hand calculation, it is a tougher situation, tough situation.

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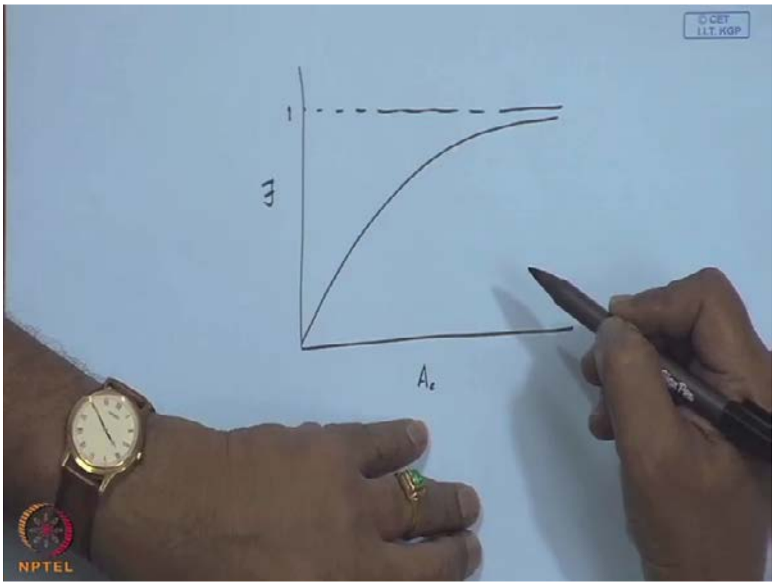

So, one would go for a little programming, but then once it is done its quite easy to calculate the yearly solar load fraction, that is ultimately by making 12 monthly calculations we are in a position to get area verses solar load fraction, something like this. This is unity and I can do whatever optimization are whatever studies one like to have by changing the system parameters, say this is the storage or the flow rate or the heat exchanger size, location, area, area of course, is the main thing and collector parameters. So, we will talk little more about the collector performance parameters and their influence on the parameters when we talk about little bit of economics in the next lecture.

Thank you.