Elements of Solar Energy Conversion
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Lecture - 19

Hello and welcome to this series of lectures on Elements of Solar Energy Conversion. Today, here we are at lecture number 19.

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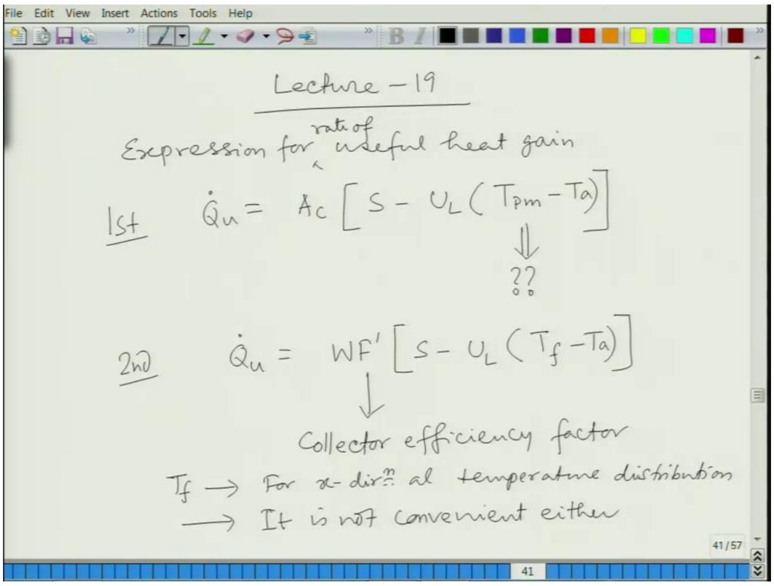

So, so far, we were analyzing the flat plate solar collector, the temperature distribution, and its relationship with the useful heat gain. So, what we obtained so far that the expression for the useful heat gain or rather the rate of useful heat gain. So, few expressions we obtained so far.

One is this Q_u equal to the area of the collector multiplied by absorbed radiation minus the loss coefficient, which is multiplied by the average temperature difference between the plate and the ambient.

So, this is the expression that is the most fundamental or most basic expression we started with while we started looking at the flat plate solar collector. But the problem in this expression is this quantity T_{pm}, which is the mean plate temperature which is unknown.

So, that is why we needed to have alternative expressions. So, this is the first expression we obtained. And the second expression that we obtained was the useful heat gain in terms of the collector efficiency factor. So, $W * F'$ then the temperature difference was not between the plate and the ambient, but between the fluid and the ambient. So, this is the F', the collector efficiency factor.

So, this we got, this T_f is again the problematic quantity, we assumed for x directional temperature distribution. We assume that this T_f is known at a particular location in the pipe, and that is how we express the useful heat gain by this expression. So, we have also seen that it is not convenient either. What is the problem? Because the fluid temperature also is changing along the length and you do not know what the value is, you do not have a common value.

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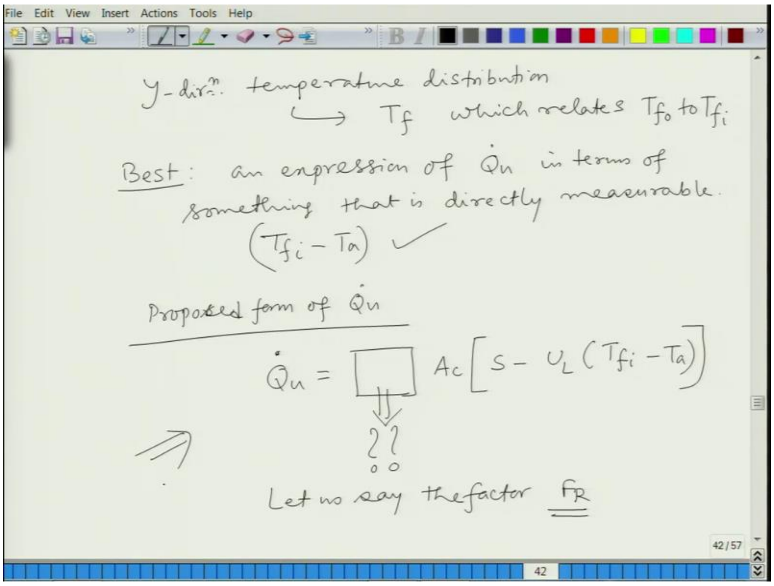

So, that is why we needed to have several other expressions. We had to do the y-direction temperature distribution; we had to look at it. So, which is x and which is y, I am not repeating it here, please look back at our earlier lectures, and you will know the y-direction is along the fluid flow direction.

So, this y-direction temperature distribution gives us a functional form of T_f, which relates the outlet fluid temperature T_{fo} to the inlet fluid temperature T_{fi}. This is the expression that we derived in the last lecture.

But the best thing what we can think of is an expression of the rate of useful heat gain $\dot{Q}_u$ in terms of something that is directly measurable. What is that? The inlet fluid temperature T_{fi} that is directly measurable you know what fluid or what temperature the fluid is going into the collector and the ambient temperature. So, if we can express the Q_{ui} in terms of this difference T_{fi} minus T_a, then it is the best thing that we can obtain.

So, so far, we did not have, or we do not have, any expression in this kind of relationship. So, what we can propose, so, proposed form of Q_u we can write $\dot{Q}_u$ is some factor which we do not know multiplied by the collector area and multiplied by the $S - U_L(T_{fi} - T_a)$. So, this is what we want. But what factor will come here is not known, that is our goal, and that is how we will proceed.

So, let us say this factor, this unknown factor is F_R. We will see that why that R, what that R stands for. But let us say that for now, it is an unknown factor which is F_R.

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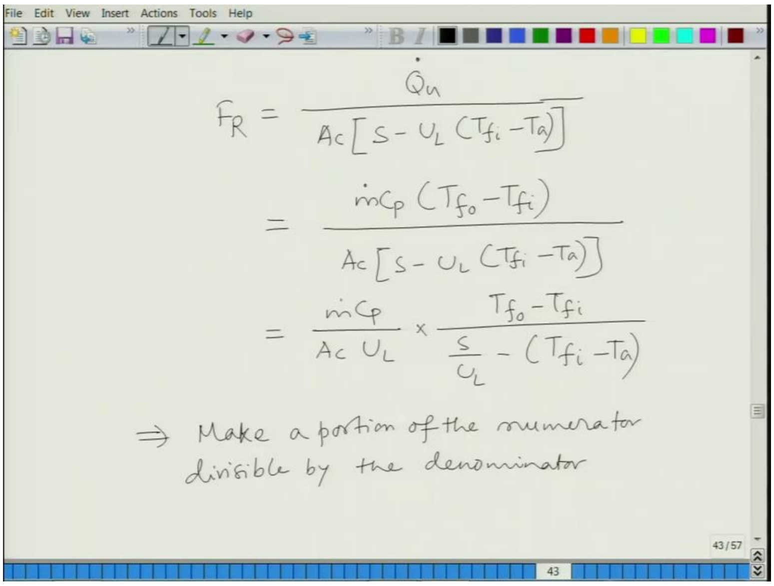

So, from the expression itself, what can we write?

$$F_R = \frac{\dot{Q}_u}{A_c(S - U_L(T_{fi} - T_a))}$$

We have done nothing but just rearrange the equation to write it in terms of F_R.

Now, this $\dot{Q}_u$ you can write absolutely in terms of the fluid heat, the fluid heat gain. So, the temperature difference between the inlet and outlet of the fluid and the mass flow rate specific heat of the fluid. So, $\dot{m}C_p(T_{fo} - T_{fi})$ that is an absolutely acceptable form of $\dot{Q}_u$. So what you are writing in terms of the fluid inlet and outlet temperatures only and the denominator does not change.

So, now, what can you do? You can take out a few of these non-temperature things and write it in terms of temperature only. And the rest of the things is in terms of temperature. So, just simple algebra, we did.

Now, what will we do? We will use some addition and subtraction to the numerator so that we can get a similar form as in the denominator. So, the goal is to make a portion of the numerator divisible by the denominator. Why will you do that? Why we are doing it will be very apparent when we will do it.

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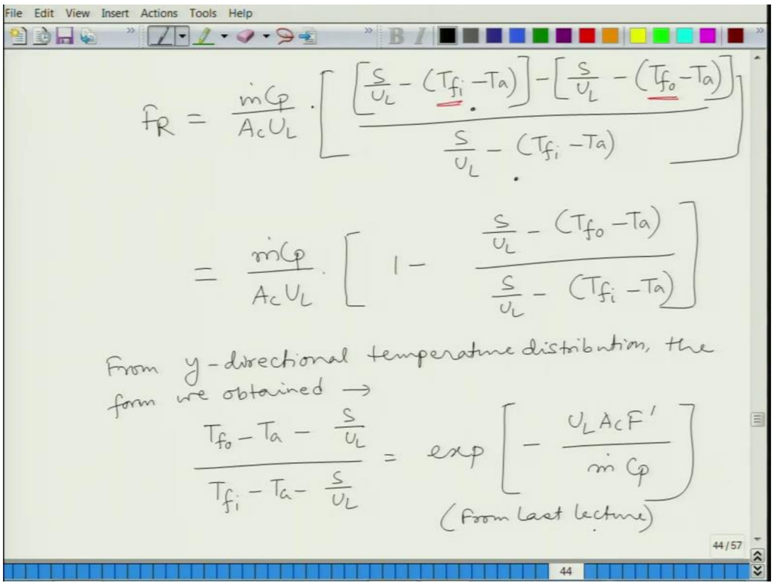

So, now, what we can write the expression F_R, we can write $\frac{\dot{m}C_p}{A_c U_L}$, this is the pre-factor. And now, the numerator will change like this $\frac{S}{U_L} - (T_{fi} - T_a)$. So, this is the denominator part we have written it directly. Now, we have to see the numerator part is balanced.

So, we have added $\frac{S}{U_L}$So we have to subtract it, and we have added T_a, the ambient temperature, so we also need to subtract it. So, now, you can see, let me write it completely the denominator is $\frac{S}{U_L} - (T_{fi} - T_a)$.

So, nothing more we did. We just did some algebra on the numerator, and you can see that in the numerator, we had $(T_{fo} - T_{fi})$. It is still there $(T_{fo} - T_{fi})$, and all the other things cancel out, $\frac{S}{U_L}$ cancels out, and T_a that part also cancels out.

Now, once we have done that, we can see the first term here, and the denominator is the same. So, we can write $\frac{\dot{m}C_p}{A_c U_L}$ and within parenthesis, we can write $1 - \frac{\frac{S}{U_L} - (T_{fo} - T_a)}{\frac{S}{U_L} - (T_{fi} - T_a)}$. Simple algebra, we did.

$$\frac{T_{f,0} - T_a - \frac{S}{U_L}}{T_{f,i} - T_a - \frac{S}{U_L}} = exp(-\frac{U_L * A_c * F'}{\dot{m} * c_p})$$

So, this is from the last lecture.

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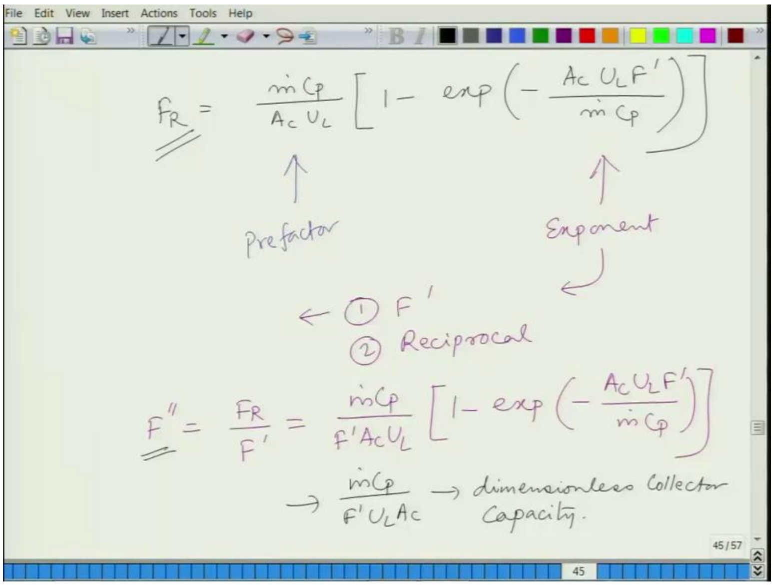

Now, we will be going to use this expression. So, if we use that expression, then this F_R becomes

$$F_R = \frac{\dot{m}C_p}{A_c U_L}(1\text{-}\ exp(-\frac{U_L * A_c * F'}{\dot{m} * c_p})$$

So, from the last lecture expression that we derived, we have used that in the formulation of F_R.

Now, I bring your attention to this pre-factor. This is the pre-factor, and this is the exponent. Do you see any similarity between these two terms, the pre-factor, and the exponent? They are very similar. The only difference is it's reciprocal; that means one over the other, and we have another F prime inserted there in the exponent. So, the exponent is the difference in F' and reciprocal; that means one over x right. So, what can we do?

We can include that F' thing and derive another factor F'' to be $\frac{F_R}{F'}$. Then, what can we write? This pre-factor will also have the F' because we have divided the whole expression by F'. So, now, we have 1 over $exp(-\frac{U_L * A_c * F'}{\dot{m} * c_p})$, you agree to this.

So, now both the pre-factor and the exponent are similar but only reciprocal. So, what can you write? This thing $\frac{\dot{m} * c_p}{U_L * A_c * F'}$, this is called dimensionless collector capacity. What do you mean by collector capacity? Collector capacity means, if you install a solar flat plate collector, it will give you hot water. So, how much hot water and with how much amount of temperature rise that is your collector capacity right.

So, you can see this expression contains $\dot{m}$ which is the mass flow rate specific heat and the heat loss factor collector efficiency factor, and the collector area. So, this is nothing but a dimensionless collector capacity factor. So, I insist that you go and check whether this is actually dimensionless or not. Do not believe me. Just go and check for yourself whether it is dimensionless or not. It is important.

So, now, we have multiple factors. This F_R, even if we did not say what that factor means, it was just a placeholder. So, if we look at so, here it was just a placeholder F_R. And then, we derived an expression for that, and also at the end, we have also introduced another thing which is F''.

So, it is important now, we have collected a few of these factors and also expressed useful heat gain with these factors. Now, it is important that we summarize them all together; otherwise, it becomes difficult which factor relates to what.

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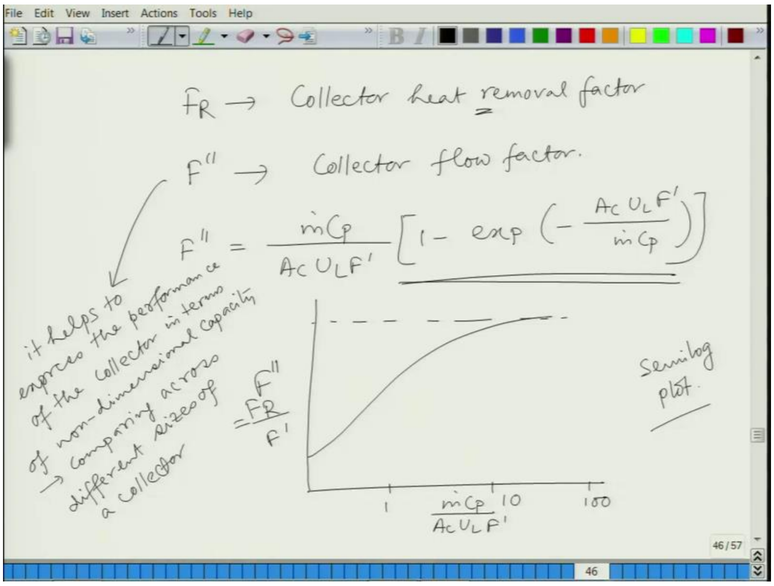

So, first thing this new factors, let me just tell them what names we call them by. F_R is called the collector heat removal factor. So, this R, subscript R stands for this removal. And this F'' is called the collector flow factor.

Why do you call flow factor? Because it includes the mass flow rate quantity, and that is why it is used to normalize between different sizes of solar collectors. So, if you have a big solar collector, if you have a small one, how do you compare their performance? That is why this collector flow factor comes into the picture?

These are the names. Now, let me just see how this expression looks like. So, the final expression

$$F'' = \frac{\dot{m}C_p}{A_C U_L F'}(1- exp(-\frac{U_L * A_C * F'}{\dot{m} * c_p})$$

So, this is the final expression. Now, if you plot it with this dimensionless collector capacity F'' which is $\frac{F_R}{F'}$.

So, you can see that it will be asymptotically equal to 1 when we have the dimensionless capacity to be large enough. So, it will look like this, and this is in a log plot. So, if this is 1, this is 10, this is 100; so, it is a semi-log plot, and this is an exponent expression, so it is useful to plot it in a semi-log plot.

So, here I should write that this collector flow factor, what it does? It helps to express the performance of the collector in terms of non-dimensional capacity. So, when you have a non-dimensional capacity, you can compare across different sizes of the collector, so which helps in comparing across different sizes of a collector.

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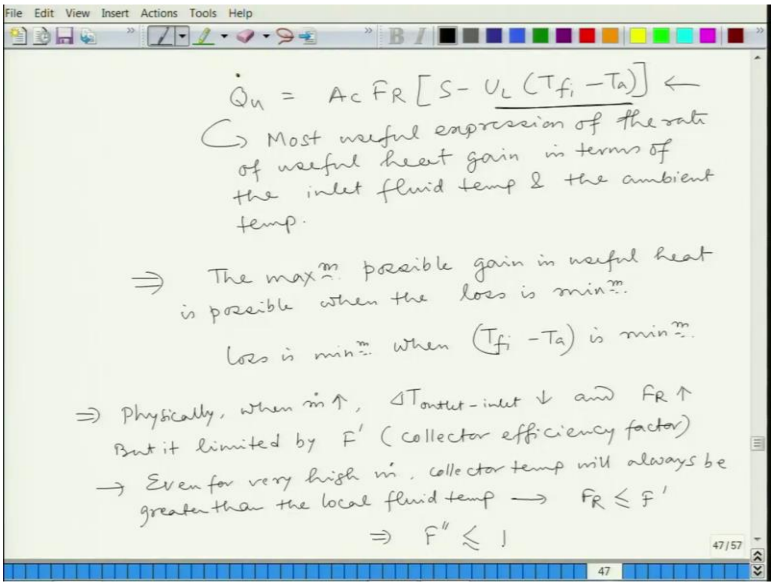

So, now, we have to somehow summarize what we did by all this thermal analysis that we did for the flat plate collector. So, the most useful expression that we obtained so far is the

$$\dot{Q}_u = A_C F_R(S - U_L(T_{f\iota} - T_a))$$

This is the most useful expression of the rate of useful heat gain in terms of the fluid inlet temperature and the ambient temperature. That is what the collector heat removal factor does.

So, here I want to bring your attention to the heat exchanger theory that you have learned in your heat transfer courses. So, there you have seen that there was one quantity called heat transfer effectiveness. So, that effectiveness relates you to the actual heat transfer, to the maximum possible heat transfer right, that is the effectiveness quantity we have seen.

So, here also this is at the start only I have told you that solar flat plate collector is nothing but a heat exchanger, but a little bit complicated heat exchanger you can say, where most of the parameters are unknown, and that is why all this complicated formulation is required to analyze it properly.

So, if we bring down that heat transfer analogy again, we can write that the maximum possible gain in useful heat is possible when the loss is minimum right. That is the basic underlying philosophy, that if you want to maximize the gain, you have to minimize the loss. Now, in the above expression here, you can see that the temperature difference comes with the loss factor U_L.

U L is the loss factor, and that particular part is minimized when you have $T_{fi} - T_a$ to be the minimum right. So, the loss is minimum when $T_{fi} - T_a$ is minimum, is not it? So, that is the minimum loss point that we will compare with the actual heat gain to get the effectiveness. So, now let us summarize. We have seen all the concepts; now, we will summarize how to use them.

So, here what is happening physically, when your mass flow rate increases, so this $\Delta T_{outlet - inlet}$, so the temperature difference between the outlet and inlet this drops right, and F_R increases. But this increase is limited by F', so this is collector efficiency factor. So, even for a very high mass flow rate, collector temperature will always be greater than the local fluid temperature. And that is why F_R this collector heat removal factor is always less than equal to F'.

And that what sets the limit for F double prime, which is always less than equal to 1. That is what we have seen in the earlier plot.

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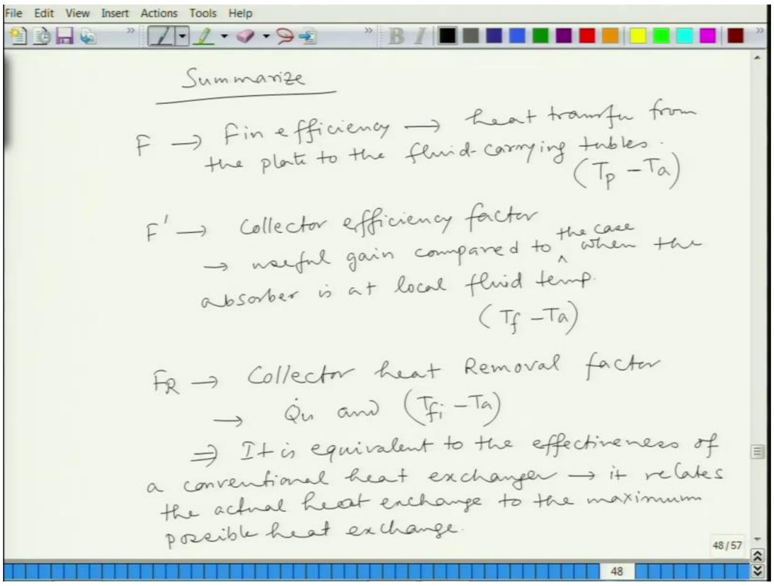

So, just to summarize this different F: The first one we have seen is simple F which we called fin efficiency. And what does it relate to? It relates the heat transfer from the plate to the fluid-carrying tubes. So, that is the first step we have looked at its fin efficiency.

Now, the next one was the collector efficiency factor which is designated as F'. Now, what it does? It relates useful heat gain compared to when compared to the case when the absorber is at local fluid temperature. So, this relates to the useful heat gain in terms of $T_f - T_a$. This one, the first one, was $T_p - T_a$ that is the relation. Now, the collector efficiency factor F' brings it to $T_f - T_a$.

And the collector heat removal factor is the new one collector heat removal factor, so it brings this Q_u, and it relates Q_u and this $T_{fi} - T_a$. So, we are not interested in the fluid temperature anywhere but the inlet. That is how the F_R came into the picture. So, what I was trying to tell you earlier that it is equivalent to the effectiveness of a conventional heat exchanger in terms of it relates the actual heat exchange to the maximum possible heat exchange.

That is the definition of heat exchanger effectiveness. And collector heat removal factor F_R does exactly the same thing.

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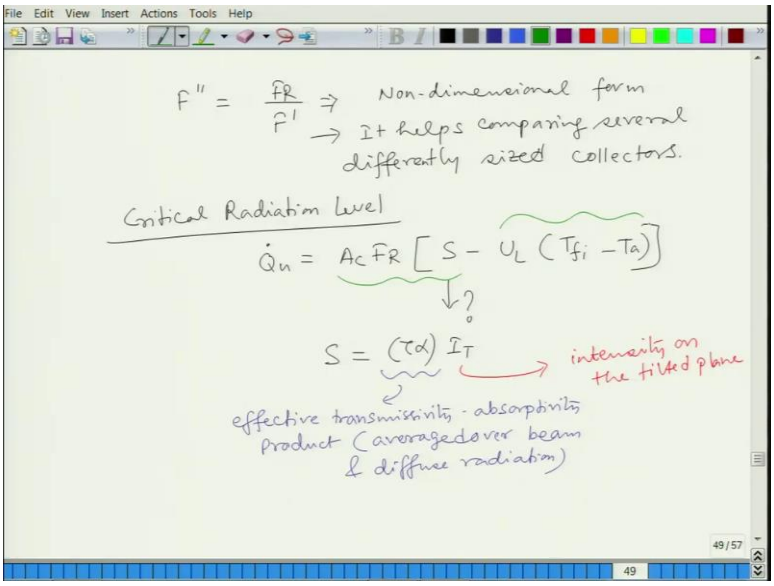

And the last one is F double prime which is F R divided by F prime, and it is a non-dimensional form of the same equation which the useful heat gain in terms of the collector heat removal factor F double prime makes it a non-dimensional equation. And that is how it helps to compare several differently sized collectors.

Now, before I move on, I want to say something about the critical radiation level. So, we have seen that the useful heat gain rate can be written in terms of the collector heat removal factor, which is

$$\dot{Q}_u = A_C F_R (S - U_L (T_{f\iota} - T_a))$$

This is the most useful form of useful heat gain.

Now, what is this S? S is the rate of absorbed heat from the solar radiation right. So, we can write it in terms of this effective ατ into the intensity on the tilted plane. So, this is nothing but S, and here this thing is the effective transmissivity, absorptivity product. And here, we are not distinguishing between the beam part and the diffuse part; we are taking an effective value according to the average absorption and averaged over the beam and diffuse radiation.

And the other part is the intensity on the tilted plane right. So, this is S. Now, and you may have a situation where you actually have very low intensity, and still you are running the flat plate collector. So, what would be the consequence? Let us see that.

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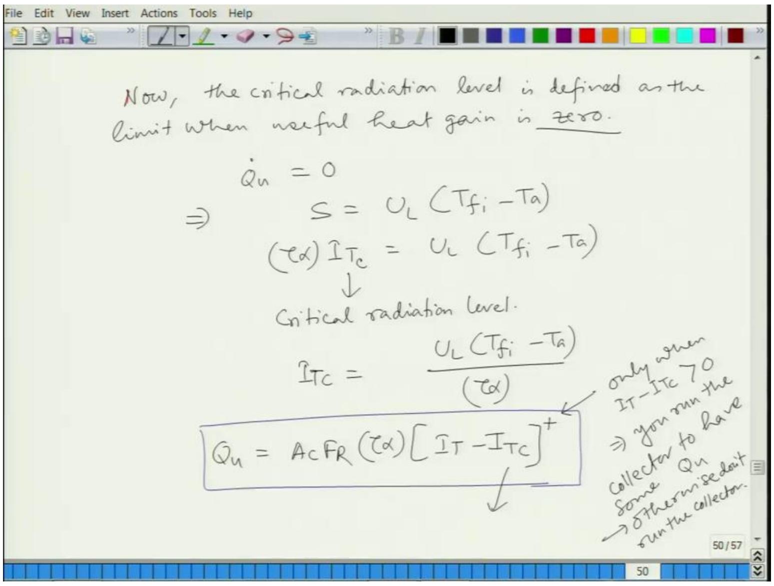

Now, let me write that the critical radiation level is defined as the limit when useful heat gain is 0. So, here in this expression, you can see that this first part is the gain and the second part tells you about the loss right. Now, when this gain and loss are equal, Q_u will be 0.

So, when Q u equals 0, then what can we write? We can write that $S = U_L(T_{fi} - T_a)$, the gain will be equal to the loss. And if you write this part and this is for critical, C for critical will be equal to $(T_{fi} - T_a)$. So, this stands for critical radiation level. So, which you further can write in terms of I_{TC}

$$I_{Tc} = \frac{U_L(T_{fi} - T_a)}{\alpha\tau}$$

So, you can see that if the solar intensity on the collector has this I_{TC} value, you are not gaining anything; you are just gaining 0 because whatever you are gaining is being lost to the atmosphere. So, that is how we find the critical intensity level below which you just cannot run the collector. If you run it, you are expanding energy in running it; you have to run the pump.

So, you are expending energy, but you are not gaining anything. So, what should you do? You should only run the collector when your intensity is above this critical value, is not it?

So, what we can write this Q_u, I_{TC} and positive, we put this sign positive here. What does it tell? That only when this $I_T - I_{TC}$ is greater than 0; you run the collector to have some Q_u, otherwise do not run the collector, It will be a loss for you.

So, that is why this particular for most of them or for any solar collector you if you buy from the market, it will tell you what would be the I_{TC} for that particular collector. That will tell you that below that level, you do not run it.

You just let it stand there, do not run fluid through it. Now, what we will look at few variations of the flat plate collector.

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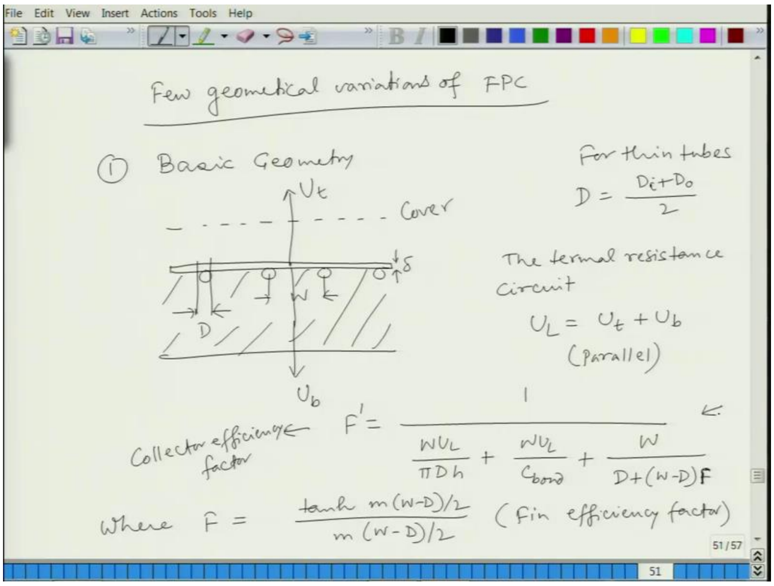

So, few geometrical variations of flat plate collector: So, we have completed the basic geometry, we have completed the analysis. So, we can use those analyses directly. And what can we write? So, what is the first one is basic geometry. Let me just summarize the last few lectures.

So, this is the plate where you have these tubes. The plate has a certain thickness; let us say this thickness is delta. And the pitch of this tube is W, and for each tube, we have sum D. So, earlier, we distinguish between the D outer and D inner, but for thin tube, for thin tubes, what can we do? We can use a common D, which is $\frac{D_i+D_o}{2}$. So, that value is our D.

And what have we seen? That this bottom portion is completely insulated, and we have still had a certain loss from the bottom, and we have a cover system here placed on, it is the cover, and through it, we have an effective loss coefficient U_t top loss coefficient. Now, for this basic geometry, the thermal resistance circuit tells us that our U_L will be equal to U_t plus U_b because they are connected parallelly.

So, if that is the case, we have derived the expression for this collector efficiency factor

$$F' = \frac{1}{\frac{WU_L}{\pi D h} + \frac{WU_L}{C_{bond}} + \frac{W}{D+(W-D)F}}$$

So, for collector efficiency, you need to first get the fin efficiency factor. And where this fin efficiency factor you have obtained the expression. And this is called the fin efficiency factor, and this is called the collector efficiency factor.

So, we have written nothing new. This is the expression we derived for the last couple; I mean few lectures, 2- 3 lectures.

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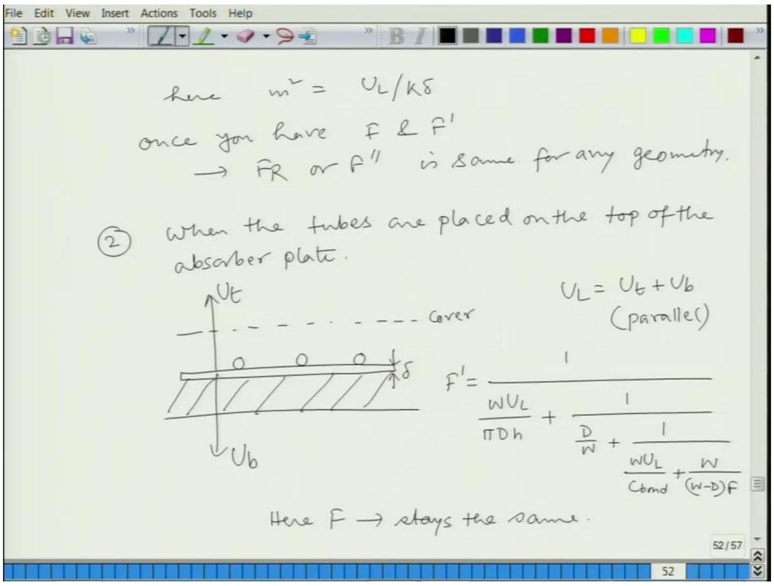

And here, this $m^2 = \frac{U_L}{K\delta}$. And once you have this F and F,' the transition from here to find F_R or F'' is the same for any geometry. So, I am not writing that. I am only going to look at if the geometry is changed how your expression for F and F' changes from that from there F_R and F'' have obtained exactly the same manner.

Now, let us look at the next variation in geometry when the tubes are placed on the top of the plate top of the absorber plate. That is also a possibility. So, here again, we have the same thing, everything same, only this is completely insulated. And the tubes are on the top of the plate, not at the bottom of the plate, but on the top. And then you have this cover. And you have this U_t and U_b. Again, this $U_L = U_t + U_b$ because you have a parallel connection.

And the expression for that gets affected is F' that the collector efficiency factor. And we are not going to derive it, but we are going to simply write it.

So, now, you see the when the tubes are at the bottom of the plate, you have this particular expression of a prime right. But now you have a separate expression of a prime because the heat transfer the resistance circuit itself changes. Now, you are exposing the tubes directly to the loss of the ambient through radiation, and it also exchanges heat with the cover through radiation as well as convection.

And here, this fin efficiency factor stays the same. So, how from the plate to the tube heat moves that part stays the same, but from there how it is exchanging heat with the fluid and releasing that heat to the or losing the heat to the ambient that part changes due to geometry.

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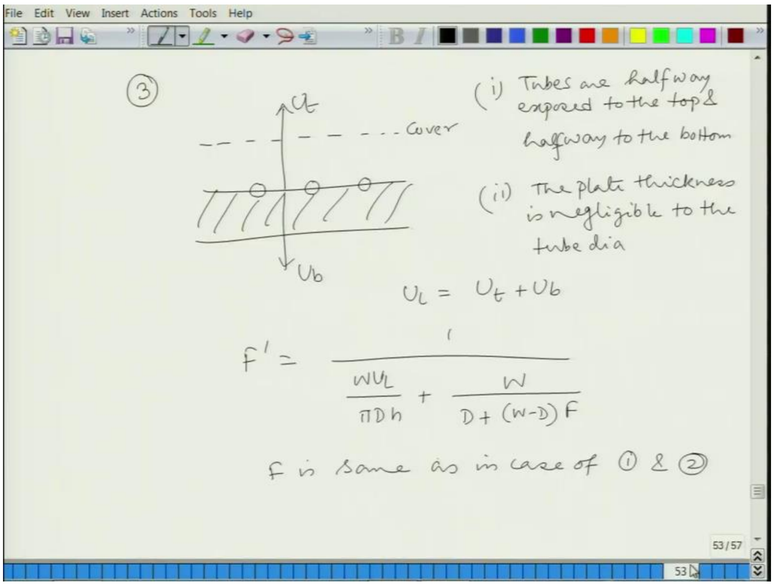

Then the third geometrical variation that we can have is tubes are halfway exposed to the top and halfway exposed to the bottom. So, if we have some plate tubes are embedded in it. So, it is halfway exposed to the top and halfway exposed to the bottom. So, tubes here are halfway exposed to the top and halfway to the bottom. And we are also assuming. So, that is the first geometrical variation. And we are also assuming that the plate thickness is negligible to the tube dia.

So, what can we do? We can redraw this with negligible tube feed thickness, and we have these tubes, and the plate thickness is negligible. And the rest of the things are the same; here you have cover, here at the bottom you have insulation. Again, you have some top loss coefficient, some bottom loss coefficient, and this total loss coefficient will be $U_t + U_b$Because they are parallelly connected.

And again, you see the difference that you obtain in the case of the collector efficiency factor F prime,

$$F' = \frac{1}{\frac{WU_L}{\pi Dh} + \frac{W}{D + (W - D)F}}$$

And F prime is the one that is getting affected by the geometry.

And once you have F prime the from there F_R the heat removal factor and F'' which is the collector flow factor all of these will be obtained by a similar method. So, now, let me show you a real picture of a flat plate collector, which I have not shown you earlier.

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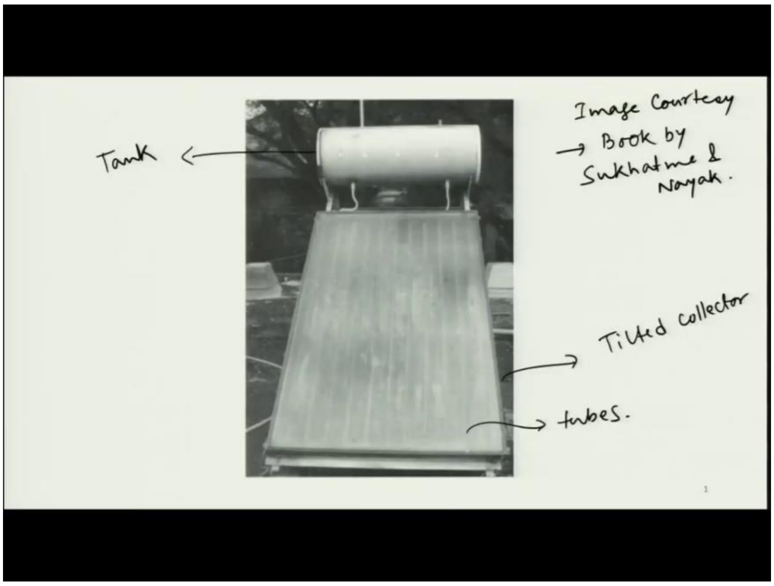

So, here we have an actual flat plate collector. And I should put the image courtesy that is obtained from the book by Sukhatme and Nayak. So, this photograph is taken from that book, and all the details of the book are mentioned in the first lecture, where all these details were mentioned.

So, here you see that we have a tank and we have a tilted collector. What would be the angle of tilt? That will depend on where you are placing it. Optimally, it should be the latitude of that place. And you have to orient the angle, orient the collector towards the equator. If you are in the northern hemisphere, it should be in towards facing towards the south, and if you are in the southern hemisphere, it should facing towards the north.

So, here you can see that these ridges are nothing but the tubes. And the whole thing is black painted, and it is under operation; that is why glare is being seen here, and that is how a flat plate collector works.

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And another thing that you can have, this array of flat plate collectors; when the temperature requirement is large, just one flat plate collector does not give you the required temperature rise.

So, what you do? You put arrays of this collector, and all of them are connected through inlet and outlet manifolds, and then you have a tank outside of this array of collectors. Again, the image courtesy is from Sukhatme and Nayak's book. So, this is for the larger capacity requirement or bigger temperature rise. Then in case of this requirement, you have arrays of these collectors.

So, let us stop it here. Then in the next class, we are going to tell you about a few more variations used in the field; for the basic flat plate collector, we have derived, described, and we have analyzed it thoroughly. So, in the next class, we will see few more practical variations that are employed, and we will also see how do we test and find the specification for a given design of flat plate collector.

Thank you for your attention.