Solar Energy Engineering and Technology
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Lecture 21
Analysis of Flat Plate Collector

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Dear students. Today we will be discussing about collector efficiency factor and collector heat removal factor of a flat plate collector.

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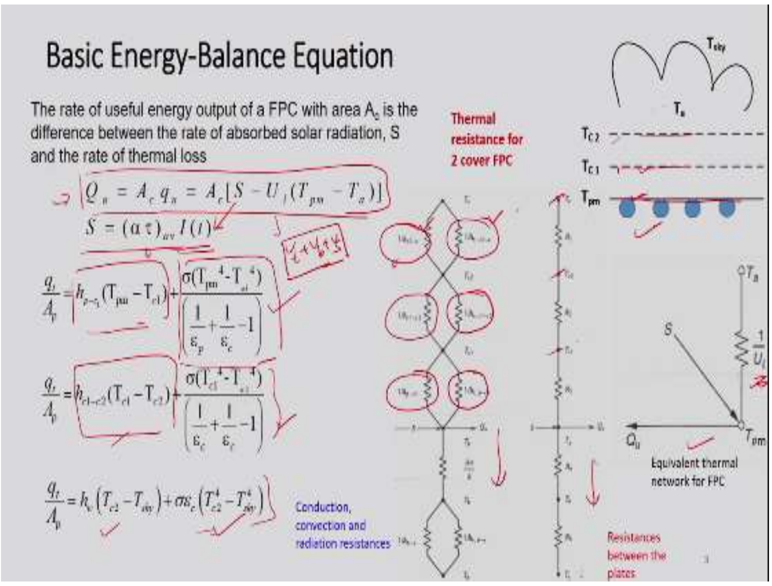

See now we know how to develop an energy balance equation. So with the previous experience we can write straight way what is the energy balance equation at the absorber plate. And also this S is nothing but the flux which is received by the absorber plate which can be expressed by using this expression. So $S = (\tau\alpha)_{av} I_T$. So earlier we have this S is a function of many parameters so we can simplify it by introducing this term $(\tau\alpha)_{av}$ in I t.

So let us now consider a flat plate collector with two glass cover system. So we have an absorber plate here this is the absorber plate and this is glass cover 1, this is glass cover 2 which is at temperature T_{c1} for glass cover 1 and T_{c2} for glass cover 2 and T_a is the ambient temperature.

So if we need to know the radiative exchange or say energy or heat transfer between two plates, if we need to understand the heat exchange between plate and glass cover 1, we have some expressions of something like this and then in between these glass cover we can use this expression to calculate the rate of heat exchange and finally heat exchange from this glass cover 2 to ambient can be estimated by using this expression.

So if we see those expressions very precisely what we can see in all the three expressions there are two components, one component is for convective part and other component is for radiative part. All the three cases we can see this is convective part and this is radiative part, this is convective part and this is radiative part. So if I am interested to draw thermal resistance of this two cover system then this may be for convective part and this may be for radiative part.

So if we start from this absorber so as we understand these two components this is for convective part, this is for radiative part when heat exchange is taking place from this absorber plate to the glass cover 1 and then from glass cover 1 to glass cover 2 we have these two expression and then from glass cover 2 to ambient we will have these two expression and then this part is towards the bottom these are the resistances. So, finally if I am interested to know the resistances between the plate so we can draw this.

This R_1 is from glass cover 2 to ambient and this R_2 is from glass cover 1 to 2 and R_3 is from absorber plate to glass cover 1 and this part is the bottom loss or bottom resistance part. So if we combine all then what we will get is a U_l. So this $U_l = U_t + U_b + U_s$ which is already been demonstrated how these are connected and how this U_t can be calculated. So, finally what we will have so this will be something like overall loss coefficient so finally this will be an overall or say equivalent thermal network for an FPC which is considered in this discussion.

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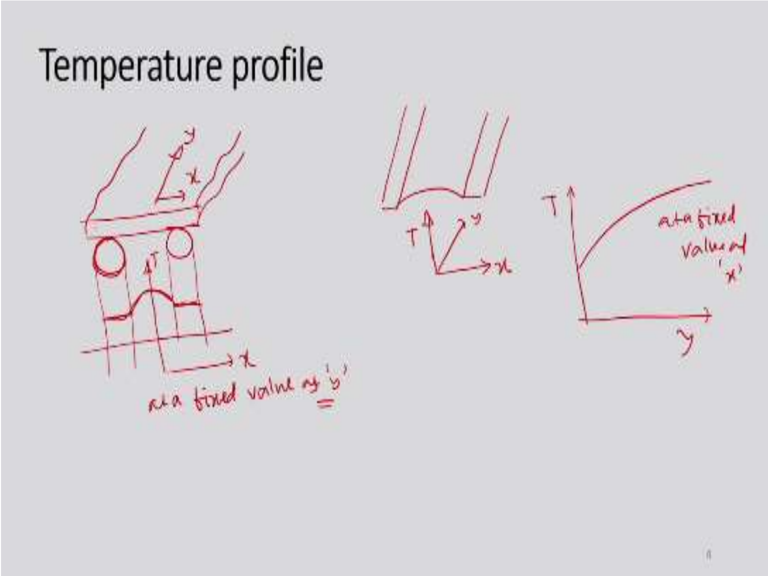

So now let us understand the temperature profile so here what I mean to say let us consider a collector of something like this and let us consider two tubes are there, just we have considered two tubes and this may be y and this may be x direction. So we are now interested to develop the temperature profile. So how it will be so temperature will be something like this.

So this is a temperature profile so this will be the temperature and we can extend this in the x direction at a fixed value of y. So this will be the temperature profile, so what is showing here, so above this or in the tubes so here temperature will be constant and in between temperature variations will be there, it will reach a maximum and then it reduces and then it will be uniform. And if I am interested to know along the flow direction then what will be the temperature profile.

Let us draw it so along the flow direction so this may be T and this may be y and this may be x. So here what I can draw this temperature profile will be this is T and then we have y and this will vary something like this. So if this will be at a fixed value of x. So this is along the flow of the fluid and this temperature profile is in between the two tubes. So these profiles are important while deriving the expression for collector efficiency factor.

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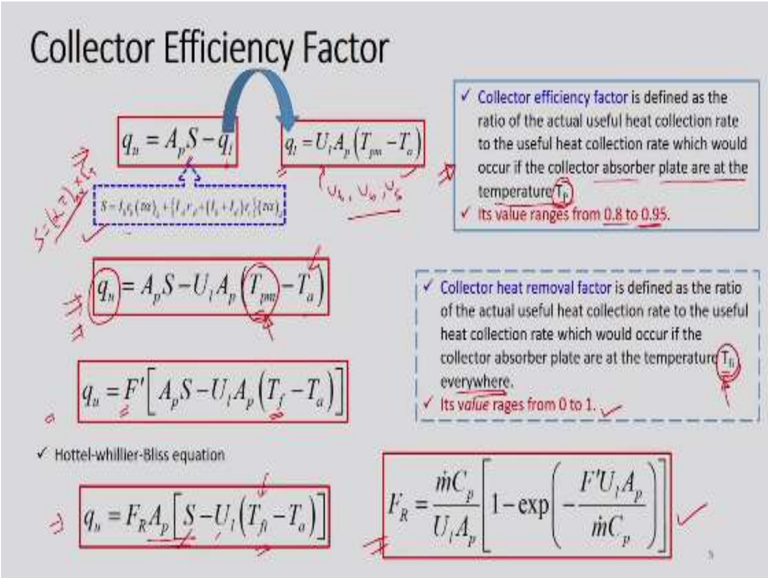

Now let us understand how this q_u are related with F' which is nothing but collector efficiency factor and an F_R which is nothing but collector heat removal factor. So already we know this expression for useful heat gain $q_u = A_p S - q_l$ which is nothing but the losses and S is a function of many variables, but we can simplify $S = (\tau\alpha)_{av} I_T$ that also we can write or we can very precisely we can use this expression and $q_l = U_l A_p (T_{pm} - T_a)$.

So if we know U_t top loss coefficient then bottom loss coefficient then side loss coefficient then we can calculate what is U_l and once we know U_l then we can calculate what is q_l. So once we know q_l, on substitution here in this energy balance equation we can calculate what will be the useful energy gain since we know this S value. Now if we substitute this value and we simplify then what we will get $q_u = A_p S - U_l A_p (T_{pm} - T_a)$.

So this expression if we need to calculate this q_u or useful heat gain we must know this temperature. Ambient temperature is always known to us, but T_{pm} it is very difficult to know this T_{pm}. So, if we do not know this T_{pm} then what will be our next target to simplify this calculation with a known value of this temperature. So what kind of temperature we can use it to simplify this equation.

So keeping this in mind these two expressions are developed this q_u is equal to F' of something and then we will have T_f this is local fluid temperature and this Hottel Whillier Bliss equation who has developed this expression for useful heat gain is a function of T_{fi}

because this T_{fi} is always known to us inlet fluid temperature we can always measure different rate of fluid in the tube.

So once we know this T_{fi} of course straightaway you can calculate what will be the q_u if we know this other parameter U_l and S. So this F' is nothing but collector efficiency factor which is defined as the ratio of the actual useful heat collection rate to the useful heat collection rate which would occur if the collector absorber plate are at the temperature of T_{fi}. So this is the definition of collector efficiency factor and its value ranges from 0.8 to 0.95.

And how to define this F_R this collector heat removal factor is defined as the ratio of the actual useful heat collection rate to the useful collection rate which would occur if the collector absorber plate are at the temperature of T_{fi} everywhere. So this temperature should be T_{fi} and here it will be T_{fi} this local fluid temperature and this T_{fi} is nothing but inlet fluid temperature and its value varies from 0 to 1. So this F_R can be expressed something like this. So we will derive one by one how this F' can be estimated and then finally how this F_R can be estimated.

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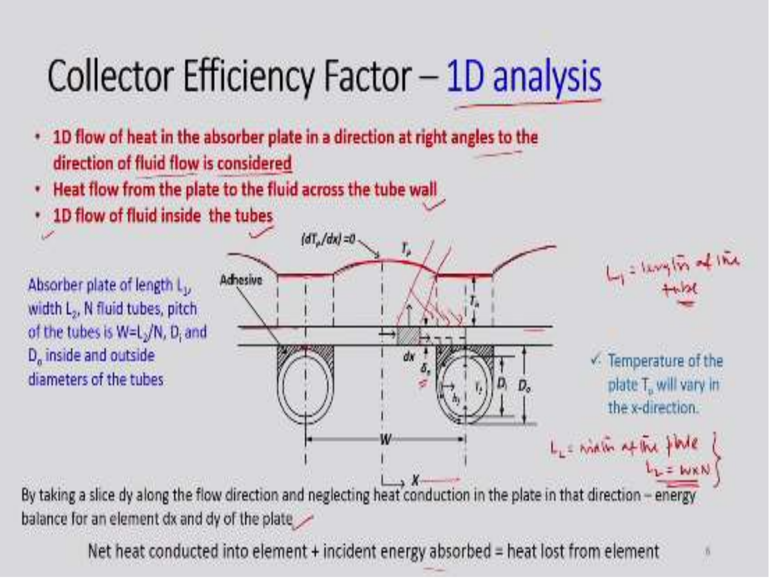

So now let us derive the expression for collector efficiency factor. So we adopt the methodology of 1D analysis or one-dimensional analysis. So in the first approach is one-dimensional flow of heat in the absorber plate in a direction at right angles to the direction of the fluid flow is considered and second consideration or second approach is the heat flow from the plate to the fluid across the tube wall and third approach is one-dimensional flow of fluid inside the tubes.

So let us consider this configuration so this is an absorber plate of say thickness dp and two tubes are considered in the collector and let the pitch be W and if we consider L_2 is the width of the plate then what we can say this $L_2 = W \times N$. So that we can do and L_1 be the length of the collector or length of the tube and D_i is the internal diameter of the tube and D_o is the outer diameter of the tube.

And as you can see these are the dashed line, these are nothing but the adhesive used to bond this tube here in the absorber plate. So let us concentrate with this small section here and this is the x and small section is dx in between these two tube and we will apply the knowledge of heat transfer here so heat will be conducted from here and then same amount of solar radiation will be falling from the top which will be transferred through this absorber plate to this fluid.

So by taking a slice this is dy so this dy will be something like this, this will be dy along the flow direction and neglecting heat conduction in the plate in the direction the energy balance for an element dxdy of the plate we can write the net heat conducted into the element so the heat conducted from this plate to this fluid and the incident solar absorbed the amount of energy which is absorbed here which is nothing but the heat loss from the element.

And here as you can see this is a temperature profile what we have discussed before. So in between the tubes variation of temperature will be there, but in the tube this temperature is not varying it is a constant because heat is carried by the fluid again this will go something like this again one more tube will come. So this will vary along x direction.

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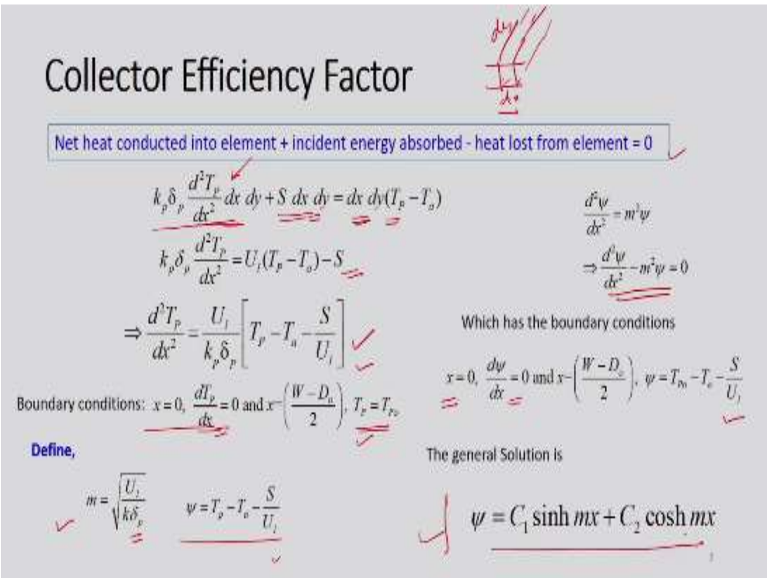

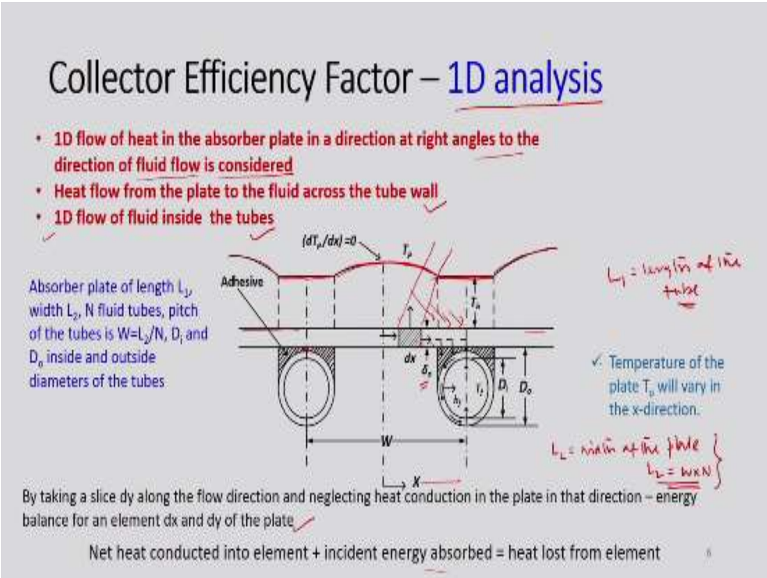

So now if we write the same expression again. This net heat conducted into the element plus incident energy balance minus heat loss from the element is 0. So what is the net heat conducted into the element? So we can use this expression for conduction and then amount of incident energy absorbed we can write S×dx×dy this is the area because we have considered this small segment so this is dx along this and then this is dy.

So it will be like something like this and this loss will be T_p so here we are using T_p instead of T_{pm} that a plate temperature we are not using m here $(T_p - T_a)dxdy$ is the area. So if we divide the entire expression by dxdy so our expression will be something like this. And again we can simplify further so $\frac{d^2T_p}{dx^2}$ will be something like this because $U_l/k_p dp$ and then if we take U_l outside then this will be free from U_l , $-\frac{S}{U_l}$.

Now there are boundary conditions so what are the boundary conditions at x=0 $\frac{dp}{dx}=0$. So as you can see here if we consider if we go back here if x is 0 may be here at this point x is 0. So this is the peak so this is gradient will be 0 here that is why $\frac{dp}{dx}=0$. So this is the boundary condition 1 and at $x=\frac{(W-D_o)}{2}$ at T_p is equal to T_o.

So that also we can see this is W this part is $\frac{D_o}{2}$ and also this part is $\frac{D_o}{2}$ so W- D so this is $\frac{D_o}{2}+\frac{D_o}{2}$, will be D so W- D so $\frac{W-D}{2}$. So that means this is the one so at T_p is equal to T_{po}. So now we will define a term called m which is $m=\sqrt{\frac{U_l}{k\delta_p}}$ and may be one term $\psi=T_p-T_a-\frac{S}{U_l}$.

So if we use this terminology in this expression then it will be something like $\frac{d^2\psi}{dx^2}=m^2\psi$. So this will be simplify like this and accordingly we have to modify this boundary conditions so at x=0 $\frac{d\psi}{dx}=0$ and at $x=\frac{(W-D_o)}{2}$, $\psi=T_{po}-T_a-\frac{S}{U_l}$. So if we solve it then we will get the general equation something like this and it is a hyperbolic function.

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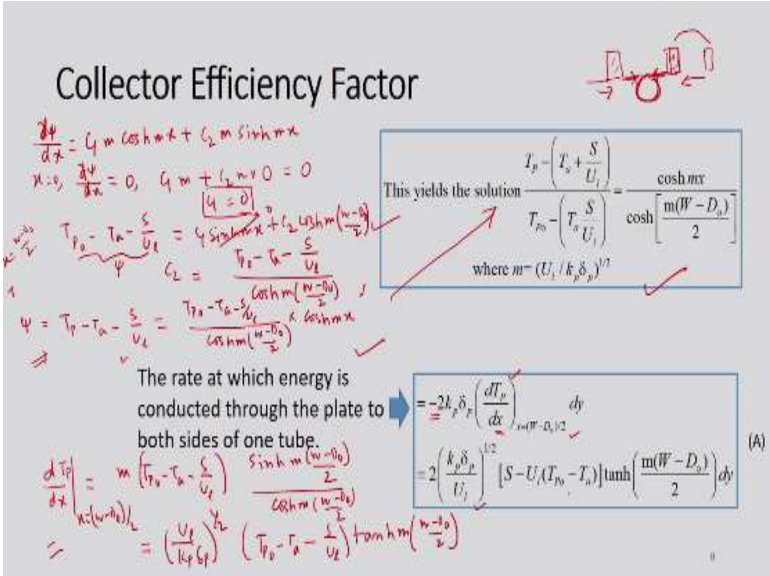

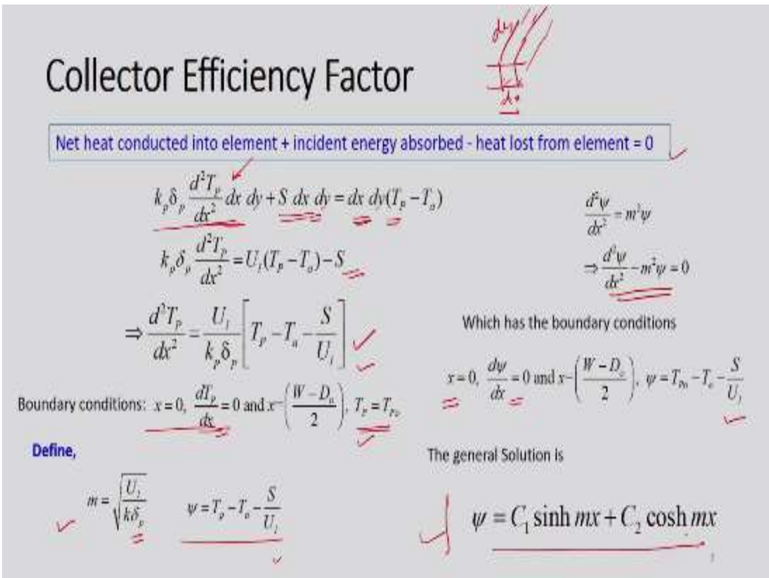

So now let us solve this expression because this will be the end of the solution. Before we come to this stage so we need to do something in between let us solve it. So we know the ψ and then we can write $\frac{d\psi}{dx} = C_1 m \cosh mx + C_2 m \sinh mx$. So we can use the boundary condition here so x=0 $\frac{d\psi}{dx} = 0$. So $C_1 m \cos 0 + C_2 m \sin 0$ so C_1 will be 0.

So again we know the first equation so we need to find out the C_2 value so how to calculate the C_2 value so $T_{po} - T_a - \frac{S}{U_l} = C_1 \sinh mx + C_2 \cosh m\left(\frac{W - D_o}{2}\right)$ so C_1 is 0 that expression we can C_1 sin of hmx because C_1 is 0 that part will be 0 and plus C_2 cos of hcos when we use the second boundary condition. So at $x = \frac{(W - D_o)}{2}$. So T will be we can go back to that this is the boundary condition.

The $\psi = T_{po} - T_a - \frac{S}{U_l}$ so that way we can use this so this is nothing ψ part. So this is first boundary condition and here $hm\frac{(W - D_o)}{2}$. So once we simplify it then what we will get C_2 will be $T_{po} - T_a - \frac{S}{U_l}$ and this will be divided by $\cosh m\frac{(W - D_o)}{2}$. So if we substitute this value in that expression for ψ this what we will get is the general solution.

So just one step I will do here so this will be $\psi = T_{po} - T_a - \frac{S}{U_l}$ is equal to so C_2 is something like this $T_{po} - T_a - \frac{S}{U_l}$ divided by $\cosh m\frac{(W - D_o)}{2}$. So multiplied by coshmx so if we divide this expression the entire expression by this $T_{po} - T_a - \frac{S}{U_l}$ so what we will get is the yield of the solution so this will be something like this.

$T_p - T_a$ so we can just modify the expression so this will be something like this. So once we are done with the solution, next phase is to calculate the rate at which energy is conducted through the plate to both the side of the tube because see we have considered this slab and then we have the tubes what is considered was here. So when we are considering this so from this side also heat will be conducted to this tube.

We are considering heat is coming from this side also we need to consider heat will come from this side because it is a nearing tube. So one more tube will be here so temperature profile will be here. So heat will be conducted from both the side to this tube. So that is why we need to multiply this expression by 2, $2k_p\delta_p\left(\frac{dT_p}{dx}\right)_{x=\frac{(W-D_o)}{2}}$.

So if we need to differentiate this T_p then again we have to use this expression so what happens this $\frac{dT_P}{dx}$ we can do here. So this $\frac{dT_P}{dx}$ at x is equal to $\frac{(W - D_o)}{2}$. So what will be the expression for this we can straight away use this expression and we can do it, if we use this here then it will be something like $T_{po} - T_a - \frac{S}{U_l}$.

So m will come out here and then it will be $\sinh m \frac{(W - D_o)}{2}$ divided by $\cosh m \frac{(W - D_o)}{2}$. So this will give a value of something like $\left(\frac{U_l}{k_p \delta_p}\right)^{\frac{1}{2}}$ and then we have $T_{po} - T_a - \frac{S}{U_l}$ is equal to $\tanh m \frac{(W - D_o)}{2}$. So now you can simplify it, since you know this and then already k_p dp is multiplied here so we can simplify it and then finally what we will have this $\sqrt{\frac{2k\delta_p}{U_l}}$ will come here and then other expression will be same as this expression.

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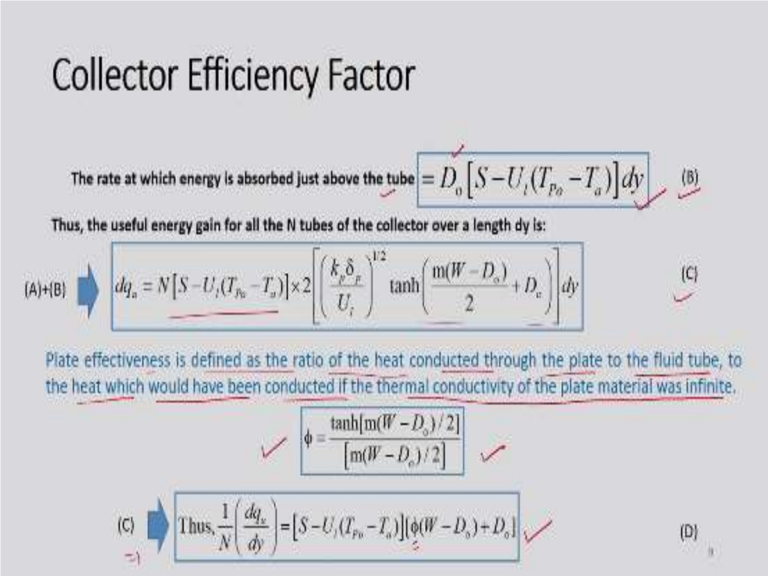

Now the rate at which energy is absorbed just above the tube also we know. So D_o is the outer diameter of the tube and this expression is known to us. So we can straightaway use it for calculation of rate at which energy is absorbed in the tube, just above the tube. So if we add this two expression this equation B expression and then equation A expression. So what we will have dq is equal to N multiplied by this expression.

So this is common so I have skipped one step here so since this part is common so we can take it out and we can now introduce two part in the bracket. So also this plate effectiveness is defined as the ratio of the heat conducted through the plate through the fluid tube to the heat which would have been conducted if the thermal conductivity of the plate material was infinite.

So under that consideration we can define this effectiveness. So effectiveness will be something like $\tanh m\frac{(W - D_o)}{2}$ to $m\frac{(W - D_o)}{2}$. So this can be utilized in this expression C and then we can modify this expression something like this. So this expression is in terms of rate effectiveness phi so phi is multiply here.

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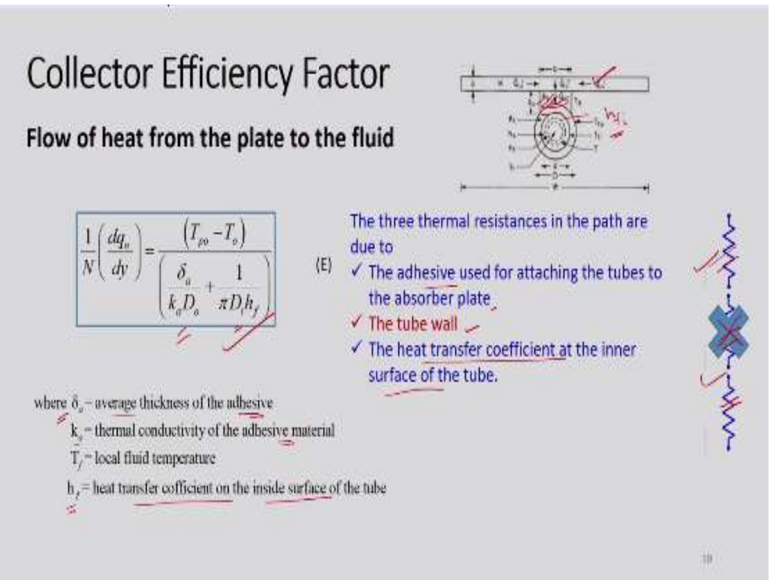

Now next step is to calculate the flow of heat from the plate to the fluid. So when we are talking about flow of heat from the plate to the tube then we must consider three thermal resistances because heat will be lost. So why this heat loss will be there, so these thermal resistances need to be considered. So what are those; the adhesive used for attaching the tube to the absorber plate, then tube wall as you can see these are the adhesive used here in this expression this is the plate and then this is the tube wall.

And then heat transfer coefficient at the inner surface of the tube so this is your inner surface of the tube. So these resistances are offered so this can be represented by this resistance line. So since the material of construction of this tube is copper, so it offers very less resistance to the heat flows so because of that this is not considered in the present derivation. So if we do not consider this and only these two are considered then our expression will be something like this.

$\frac{1}{N}\left(\frac{dq_u}{dy}\right)$ is something like $T_{po}-T_o$ to these two resistances. One is for the adhesive used and then second one is for the heat transfer coefficient at the inner surface of the tube. So this delta is the average thickness of the adhesive and k_a is the thermal conductivity of the adhesive material and T_f is the local fluid temperature and h_f is the heat transfer coefficient on the inside surface of the tube.

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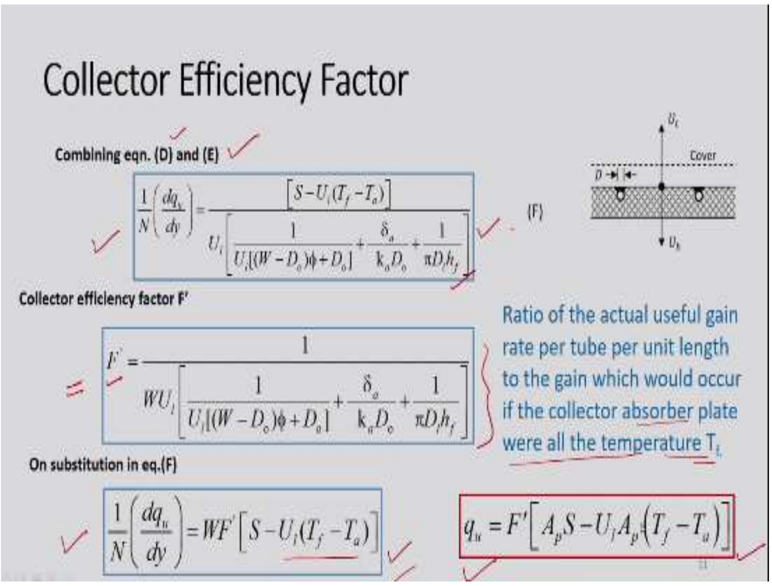

So now we can use these equations and then we can arrive at a expression of something like this. So here what we did by using this equation D and E we tried to remove this T_{po} and final expression will be something like this. Now we can define this collector efficiency factor F' is nothing but this. So which is nothing but ratio of the actual useful heat gain rate per unit length to the gain which would occur if the collector absorber plate were all at the temperature of T_f.

So now again we can simplify and we can have this equation this F' you can use in equation F then this will be a very simple equation $\frac{1}{N}\left(\frac{dq_u}{dy}\right) = WF'\left[S - U_l\left(T_i - T_a\right)\right]$. Now once you know this then from that we can calculate what will be the useful heat gain q_u is equal to F' multiplied by this expression.

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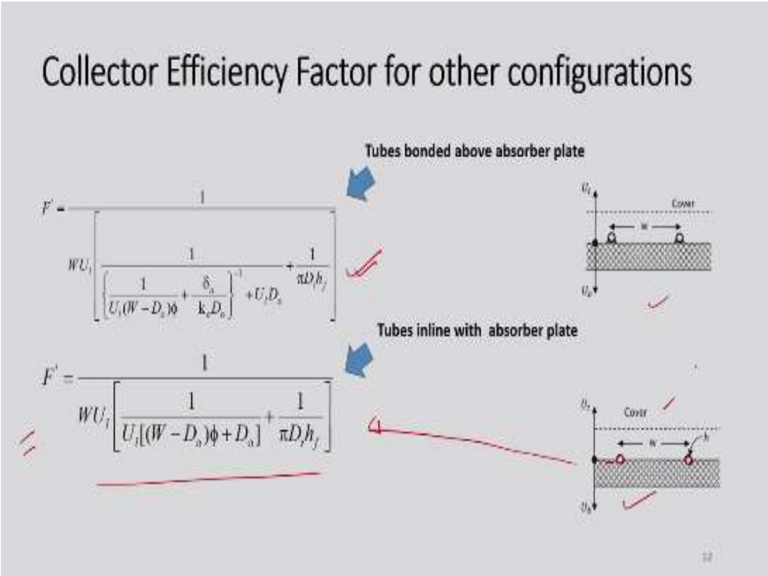

Now let us see what happens if the configuration changes. So this expression is for the tube bonded above the absorber plate so you can see the cases what we have derived just now that was for the tube which is attached below this absorber plate. Now if you see the case when this tubes are attached above the absorber plate then expression will be something like this and sometimes this inline configuration are also used in absorber plate.

So this is the absorber plate in the same line we will have this tubes. So if this is the case then we need to use the expression for F' something like this. So straight away we can use those expression for calculation of collector efficiency factor for these two configurations.

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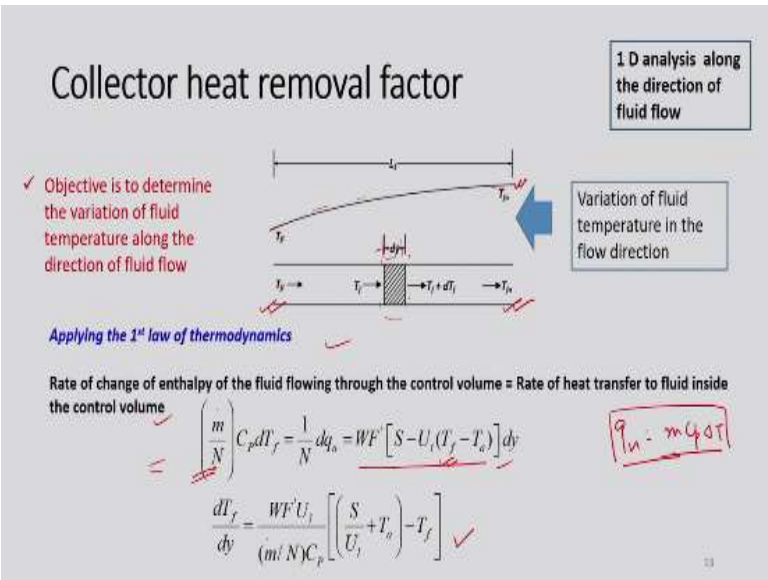

Now come to the analysis part for collector heat removal factor. So in this case also one dimensional analysis along the direction of the flow will be considered. So objective is to determine the variation of fluid temperature along the direction of fluid flow. As we have discussed the temperature variation so it goes something like this so this is an inlet of the fluid and this T_{fo} is the outlet of the fluid temperature.

So it varies something like this, at the outlet of course we will get the highest temperature. So this is the variation of fluid temperature in the flow direction. So if we consider small control volume here, this is a control volume, so dy is the thickness and if we apply the first law of thermodynamics that is the rate of change of enthalpy of the fluid flowing through the control volume is equal to the rate of heat transfer to the fluid inside the control volume.

So if we use this first law of thermodynamics then it will be something like this because we know $q_u = mC_p dT$. Since we are dealing with the N number of tubes which is attached in a flat plate collector because of that N has to be considered here and this q_u represent in terms of T_f so our expression will be something like this. So we can write $\left(\frac{dT_f}{dy}\right)$ will be something like this. Now we can derive the expression.

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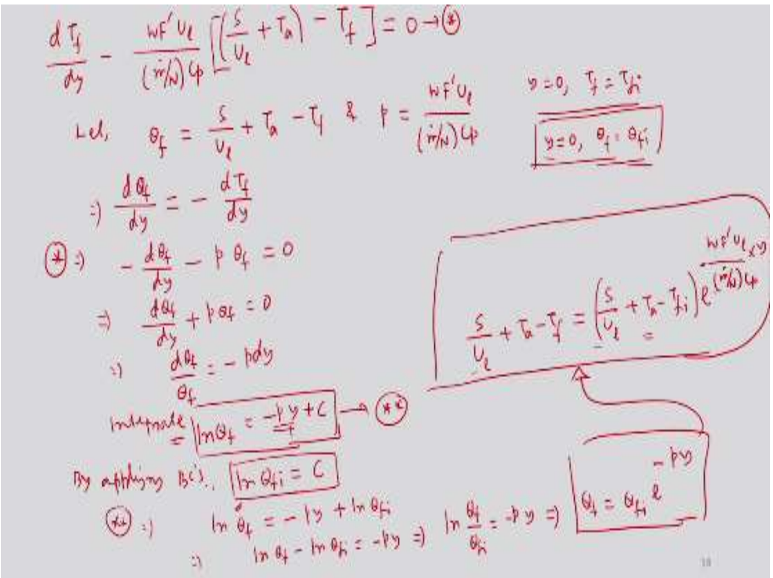

So we can write $\frac{dT_f}{dy} - \frac{WF^{'}U_l}{\left(\frac{\dot{m}}{N}\right)C_p}\left[\left(\frac{S}{U_l} + T_a\right) - T_f\right]$. So this will be equal to 0 maybe we can write this expression maybe star I will write. So now let us consider say $\theta_f = \frac{S}{U_l} + T_a - T_f$ and $p = \frac{WF^{'}U_l}{\left(\frac{\dot{m}}{N}\right)C_p}$. Now if I will differentiate it, $\frac{d\theta_f}{dy}$ then what we will have these are constant so this will be minus $\frac{dT_f}{dy}$.

So if we use the expression star here I have not yet mentioned the boundary condition we will use here. So it will be something like so boundary condition was so when y is equal to 0 then T_f is equal to T_{fi} which is obvious. So if we modify this boundary conditions if y is equal to 0 then we have $\theta_f = \theta_{fi}$. So here so equation star implies what we can write is something like $-\frac{d\theta_f}{dy}$ is equal to this part is p and again this part is θ_f is equal to 0.

So again what we can write if we multiply both side with minus 1 so df θ_f is dy then we have plus this f is equal to 0 or we can write $\frac{d\theta_f}{\theta_f} = -pdy$ and if we integrate what we will get $\ln\theta_f = -py + c$. So this is an differential equation. So this is the solution of this so on integration what we will have $\ln\theta_f = -py + c$.

Now apply the boundary conditions by applying Bc's what will happen so at y is equal to 0 this equation we need to use at y is equal to 0 $\theta_f = \theta_{fi}$. So ln of the f_i this y0 means this expression will be 0 so C will be θ_{fi}. This maybe you can write double star so now using this in double star equation this star so $\ln\theta_f = -py + \ln\theta_{fi}$.

So if we now deduct θ_{fi} from both the sides then it will be something like $\ln\left(\frac{\theta_f}{\theta_{fi}}\right) = -py$ is equal $\theta_f = \theta_{fi}e^{-py}$. So we can substitute those values p and θ here, so if we substitute this then $\theta_f = \frac{S}{U_l} + T_a - T_f$ is equal to so θ_{fi} is how much. It will be $\frac{S}{U_l} + T_a - T_{fi} = e^{-\frac{WF'U_l}{\left(\frac{\dot{m}}{N}\right)C_p}y}$ and.

So this minus is here. So our expression will be something like this.

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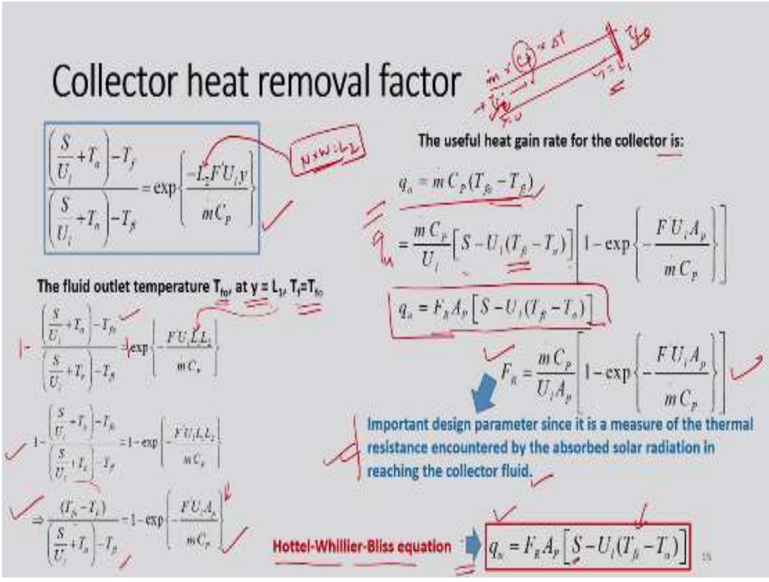

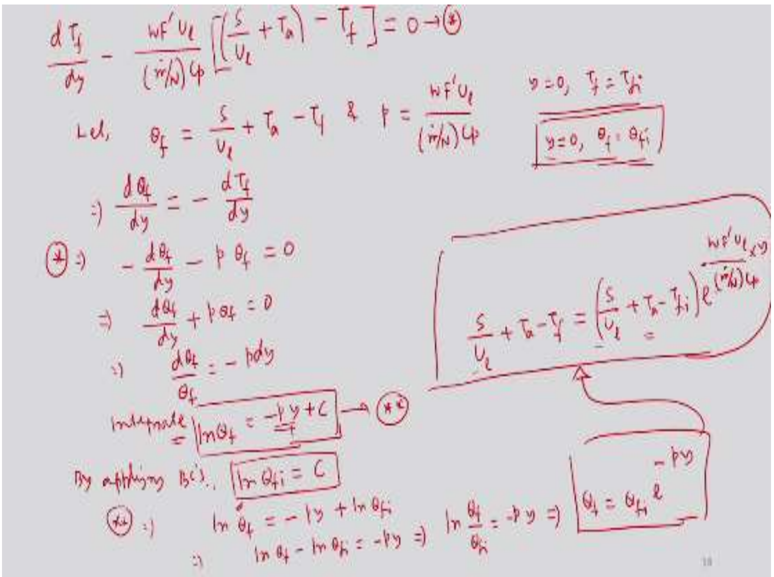

So now we move to the next slide, so if we divide both the expression by $S-U_l +T_a -T_{fi}$ then what we will have this divided by this will be this part. So that is how we will show here so this will be something like this. So this fluid outlet temperature so one more thing I missed here so here as I know N×W is L_2 so which is applied here this is applied here.

If you go back so you can see WN is the bottom side and then if you multiplied by W× N is something like L_2 that is how we can write L_2 here. Now the fluid outlet temperature T_{fo} at y is equal to L_1 so because length of the tube is L_1 so T_f is equal to T_{fo} that is obvious so tube is here. This is the so y it was 0 and when it was y is equal to L_1 so this is nothing but this is T_{fi} this is T_{fo}.

So that is how we can write this expression something like this. So this will be at here at the outlet and if it is the outlet then y will vary from 0 to L_1 so that is how it is L_1 here. Now if we deduct this expression from both side so this will be something like this so we will have this kind of expression T_{fo} - T_{fi} divided by this expression is equal to 1 minus exponential of that considered P.

Now what we were interested about this useful heat gain so this useful heat gain rate for the collector is something like this $mC_p dT$. So if some amount of mass is flowing inside this tube and C_p specific heat of fluid is known and then these two temperature inlet and outlet temperature is known, then straightaway we can calculate the useful heat gain rate for the collector which is dT.

So we can modify this expression because this is known to us now. So if we know this multiplied by this then we will have this expression. So now what we can see here this q_u is in terms of T_{fi} only we need that inlet fluid temperature. So once we know this inlet fluid temperature another expression then straight away we can calculate what is q_u which is much easier than calculating q_u in terms of mean plate temperature T_{pm}.

So this q_u is equal to $F_R A_P$ of something like this. So what is F_R now? F_R can be expressed something like this. So this F_R is nothing but collector heat removal factor which is very, very important parameter for performance of a flat plate collector. Also this is an important design parameter since it is a measure of the thermal resistance encountered by the absorbed solar radiation in reaching the collector fluid.

So why it is important you understood now and finally what expression we get is something like $q_u = F_R A_p \left[S - U_l \left(T_{fi} - T_a\right)\right]$ so q_u is related with T_{fi} and this is a famous equation developed by Hottel Whillier and Bliss and this expression also known as Hottel Whillier Bliss equation.

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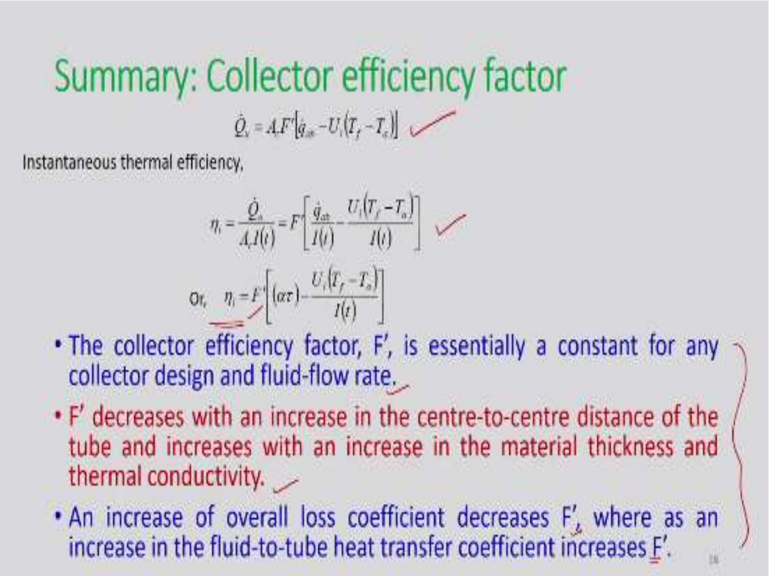

Now if we summarize about collector efficiency factor it goes something like this. We have learned this how to calculate q_u and also we can calculate instantaneous thermal efficiency. So this expression will be something like this if we express in terms of F'. So this collector efficiency F' is essentially constant for any collector design and fluid flow rate. This collector efficiency factor decreases with an increase in the center-to-center distance of the tube and increases with an increase in the material thickness and thermal conductivity.

An increase of overall loss coefficient decreases F' whereas an increase in the fluid to tube heat transfer coefficient increases F'. So these are very, very important observations so we should keep in mind why F' is very, very important as far as design of a flat plate collector is concerned.

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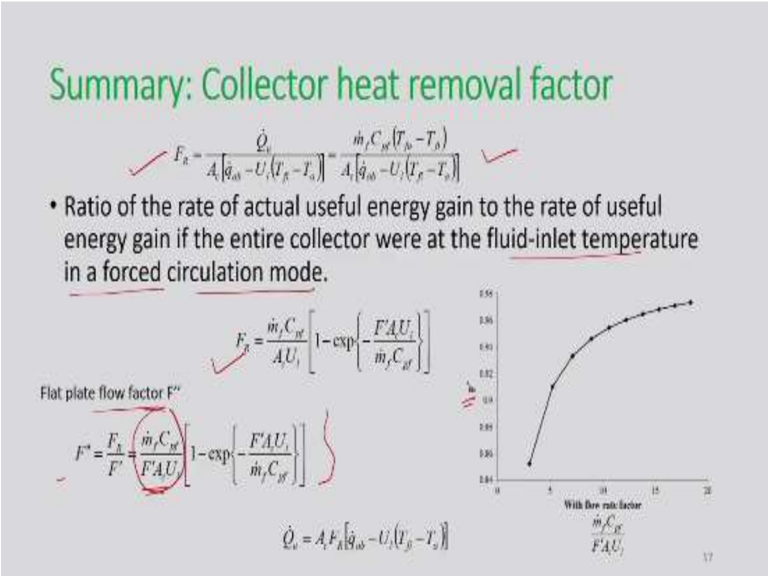

So if we summarize about collector heat removal factor so already we have defined how this F_R can be calculated and which is the ratio of the rate of actual useful energy gain to the rate of useful energy gain if the entire collector were at the fluid inlet temperature in a forced circulation mode. So this is the expression for F_R and also sometimes we can define a term called flat plate flow factor.

So this is something like F_R/ F' so this is the expression for flat plate flow factor. So if we plot the variation of F' with respect to this expression so we can get this kind of plot. So this is also important sometimes to know the variation of this flat plate flow factor with respect to this flow rate factor.

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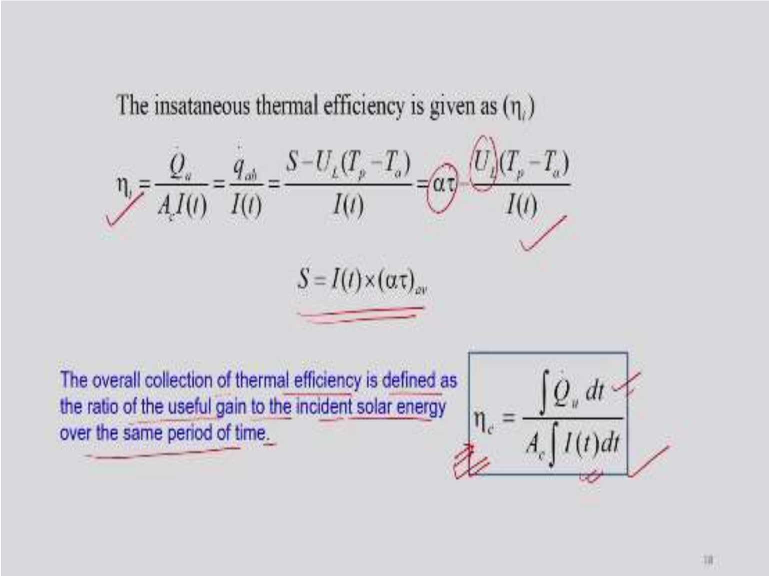

Also instantaneous efficiency is important so at any moment if we need to know the efficiency of the collector we can straight away use this expression once you know this tau alpha value and this overall loss coefficient. So this is known to us now and this overall collection of thermal efficiency is defined as the ratio of useful gain to the incident solar energy over the same period of time.

So if we have to calculate this collector efficiency we can integrate over time and we can calculate it. So this is for useful heat gain and this is for the amount of solar radiation received at a particular site, so straightaway you can calculate the collector efficiency. So this expression is for instantaneous and this is for time based efficiency or collector efficiency all we can say.

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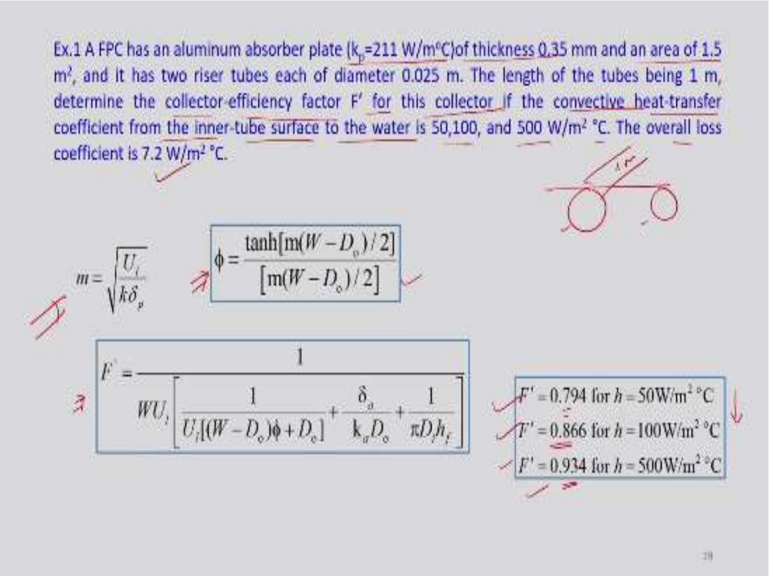

So we can solve one problem so this problem goes something like a FPC has an aluminum absorber plate having thermal conductivity 211 W/m°C of thickness 0.35 mm and an area of 1.5 m^2 and it has two riser tubes, so two tubes are there and diameter is given and length of the tube is also given this length is given it is 1 meter. Determine the collector efficiency factor F' for this collector if the convective heat transfer coefficient from the inner tube surface to the outer is 50,100 and 500 W/m^2°C.

And overall heat transfer coefficient is given as 7.2 W/m^2°C. We know the expression for m, then plate effectiveness and F' or collector efficiency factor. So once we substitute those values so we will get this kind of values. So once this heat transfer coefficient changes we can see the change in F' values. So if we can increase this F' value of course we can get the higher useful heat gain.

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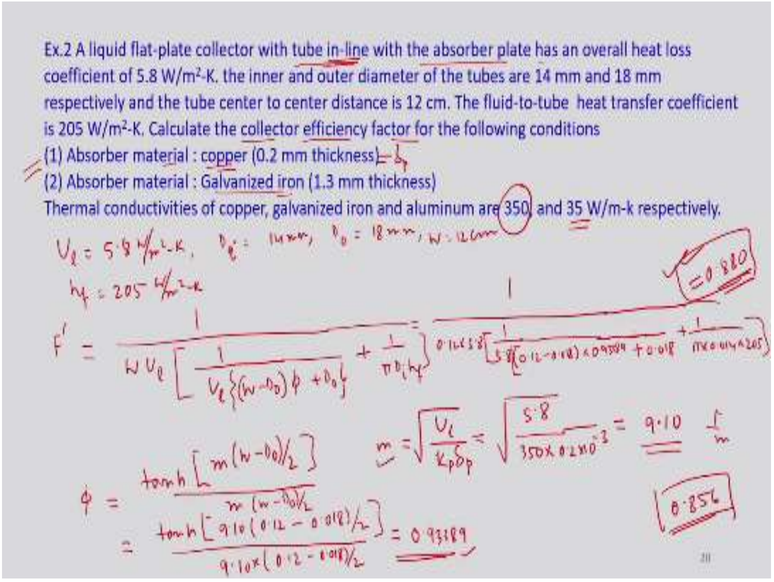

So maybe we can solve one more problem. So it goes something like this a flat plate collector with tube in-line with the absorber plate, so these configurations will be something like if you have kind of configurations. So it goes something like this, this is in-line fluids are flowing in this channel. So overall loss coefficient is given as 5.8 so this U_l is something like 5.8 W/m^2-K.

The inner and outer diameter of the tubes are given. So D_o is given as 14 mm Di and D naught is 18 mm and center-to-center distance this W is 12 centimeter. Fluid to tube heat transfer coefficient is given as 205, so h_f is given as 205 W/m^2-K. So we are interested to calculate collector efficiency factor that is F' for the configuration of something like tube in-line and absorber plate material two different materials are to be used.

So in the first case is copper having thickness 0.2 mm and second case absorber material is galvanized iron and thickness is 1.3 mm and thermal conductivity of these two materials are given. So let us start with this expression $F' = \dfrac{1}{WU_l\left[\dfrac{1}{U_l\{(W-D_o)\phi + D_o\}} + \dfrac{1}{\pi D_i h_f}\right]}$ and also we know the expression for ϕ.

So this $\phi = \frac{\tanh\left[\frac{m(W-D_o)}{2}\right]}{\frac{m(W-D_o)}{2}}$. So these values are known to us so straightaway we can calculate which is ϕ before that we must know what is m. So $m = \sqrt{\frac{U_l}{k_p \delta_p}}$. So if we substitute the values of U_l, U_l is 5.8 then what is k_p, k_p is so if we consider copper so in the first case k_p is 350 and δ_p is 0.2×10^{-3} so this thickness is δ_p.

So on substitution what will be the value of m it will be 9.10 this is the value. So this will be in 1 by meter. So if we use this m here so I will just write tanh this will be 9.1 then W is how much, it is 12 centimeter. So this will be in meter 0.12 and D_o is 18 mm so this is 0.018. So this divided by 2 and this will be m is 9.10 then we have 0.12 minus 0.018 divided by 2. So this gives a value of 0.93389.

So if we use this ϕ here and then substitute all those values. So here straightaway we can substitute those values. So 1/W value is we have $0.12 \times U_l$ is 5.8 then we will have $1/U_l$ is again 5.8 then you have I will use this then W is how much $(0.12-D_o)$ is 0.018 then ϕ how much we got already 0.93389 then we will have D_o what is the value of D_o here 0.018 then plus $\frac{1}{\pi D_i h_f}$ is 0.014 ,h_f is 205.

So this gives a value of 0.880. So if we change the value of this thickness 1.2 and material is galvanized iron and conductivity will change it will be 35. So what value we will get is about 0.856 as per my calculation. So we can see this one is always better than 856. So always we will go for this copper based absorber plate. So that is how the kind of material to be used for a particular applications will be decided by those calculations. So once we know this F' values then we can decide, so which one will be the best for the particular application, so that is what it is demonstrated in this example.

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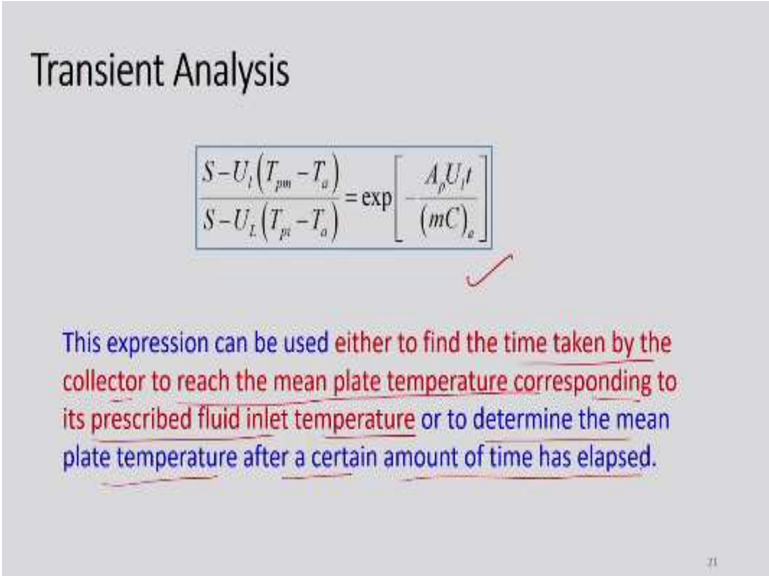

Also sometimes transient analysis is important because you need to know what is happening with time, how much time it will take to get an uniform temperature of the absorber plate. So this kind of expressions can be generated for transient analysis. So this expression can be used either to find the time taken by the collector to reach the mean plate temperature corresponding to the prescribed fluid inlet temperature or to determine the mean plate temperature after a certain amount of time has been elapsed. So straight away we can use this equation for those two conditions.

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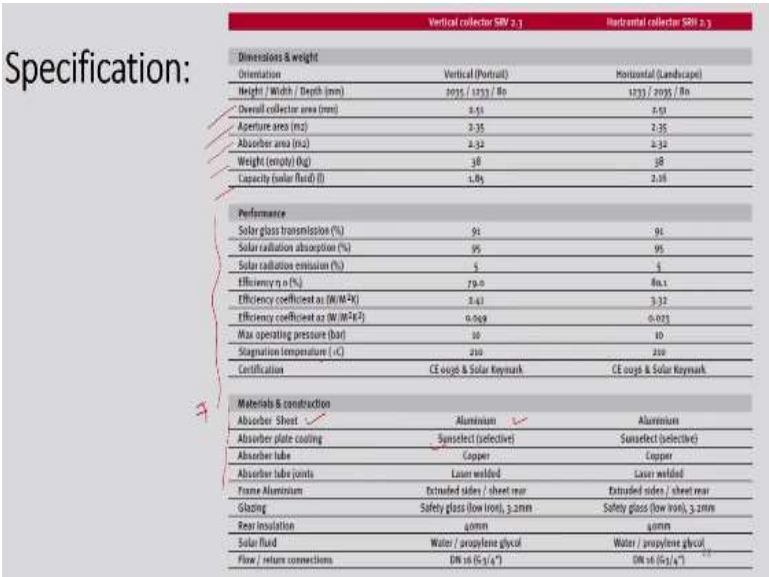

	Vertical collector SRV 2.3	Horizontal collector SRH 2.3
Dimensions & weight		
Orientation	Vertical (Portrait)	Horizontal (Landscape)
Height / Width / Depth (mm)	2035 / 1233 / 80	1233 / 2035 / 80
Overall collector area (mm)	2.51	2.51
Aperture area (m2)	2.35	2.35
Absorber area (m2)	2.32	2.32
Weight (empty) (kg)	38	38
Capacity (solar fluid) (l)	1.85	2.16
Performance		
Solar glass transmission (%)	91	91
Solar radiation absorption (%)	95	95
Solar radiation emission (%)	5	5
Efficiency η o (%)	79.0	80.1
Efficiency coefficient a1 (W/M²K)	3.41	3.32
Efficiency coefficient a2 (W/M²K²)	0.049	0.023
Max operating pressure (bar)	10	10
Stagnation temperature (°C)	210	210
Certification	CE 0036 & Solar Keymark	CE 0036 & Solar Keymark
Materials & construction		
Absorber Sheet	Aluminium	Aluminium
Absorber plate coating	Sunselect (selective)	Sunselect (selective)
Absorber tube	Copper	Copper
Absorber tube joints	Laser welded	Laser welded
Frame Aluminium	Extruded sides / sheet rear	Extruded sides / sheet rear
Glazing	Safety glass (low iron), 3.2mm	Safety glass (low iron), 3.2mm
Rear insulation	40mm	40mm
Solar fluid	Water / propylene glycol	Water / propylene glycol
Flow / return connections	DN 16 (G3/4")	DN 16 (G3/4")

And this slide shows the specifications of a commercial flat plate collector. So all the information are here as you can see like overall collector area, aperture area, absorber area, weight capacity then the solar glass transmission then solar radiation absorption, solar radiation emission then efficiency and efficiency coefficient, maximum operating pressure, stagnation temperature and then material and construction, the kind of material, absorber sheet what are the material it is aluminum, absorber plate coating.

So what kind of coating it is a selective coating we will discuss those selective coating may be in the next class. Then absorber tube what kind of tube material used as a absorber tube then frame glazing all the information we must know when we go for purchase of this kind of solar flat plate collector for may be commercial purpose or may be research purpose. So I hope by now you understand the importance of those terminologies what we have discussed. So as a layman all people know about this, but now technicality we must know how these are connected with commercial aspects.

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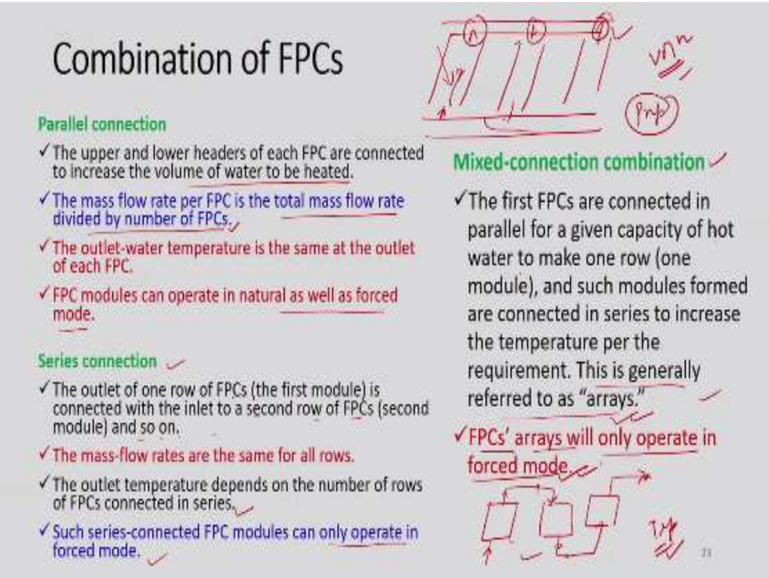

Now we will learn something about combination of flat plate collectors. There might be some cases when we need to connect the flat plate collectors in series or may be in parallel or may be both means series and parallel. So in case of parallel connections, the upper and lower headers of each FPC are connected to increase the volume of the water to be heated. The mass flow rate per FPC is the total mass flow rate divided by the number of FPCs.

The outlet temperature or outlet water temperature is the same as the outlet of each FPCs because these are connected in parallel and these are the headers. So this may be one temperature say inlet and outlet so outlet temperature will be same this outlet temperature will be same. This temperature, this temperature, this temperature will be same for all the collectors when it is connected in parallel. So this FPC models can operate in natural as well as forced mode.

This may be thermosiphonic because of this density difference mass movement of the fluid will be there as temperature increases that is called natural or if some kind of pumps another devices are used that becomes forced. So for series connection what happens this is the collector 1, this may be collector 2, so it may be inlet, this is outlet. So outlet will be connected to inlet here and then this outlet will go to the other collector. So other collector here as a inlet so that way we can maximize the temperature. So here we can maximize the volume.

And here we can maximize the temperature. So volume of water and this temperature of the water if water is a heat transfer fluid. So this outlet of one row of FPC is connected with the inlet to the second row of the FPC and that continuous as per the requirement. The mass flow rates are the same for all the rows. The outlet temperature depends on the number of rows of FPC connected in series.

So this temperature depends on the number of this kind of FPCs are connected in series. So such series connected FPC module can only operate in the force mode. So here thermosiphonic mode will not work so we need to apply some kind of active devices like pumps and of course we will have some other configurations like mixed connection combination.

So the first FPCs are connected in parallel for a given capacity of the hot water to make one row and such modules formed are connected in series to increase the temperature as per the requirement. So this is generally referred to as arrays. So we know the arrays for PV systems and we can also define similar kind of configurations here in case of flat plate collectors. So this FPCs arrays will only operate in the forced mode, we need to apply some kind of active devices.

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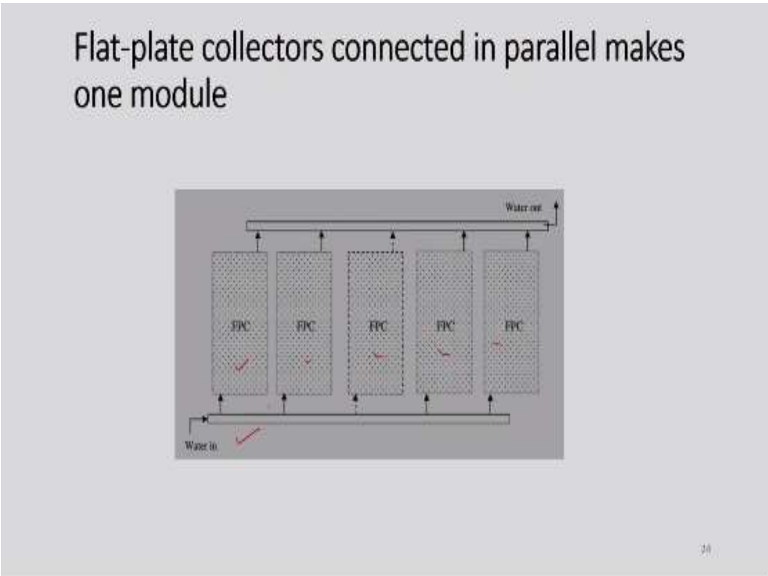

So here we can see the parallel connections so this FPC 1, 2, 3, 4, 5 these are connected in parallel so this is header and this is one more header this is for inlet, this is for outlet so this temperature are same for all the collectors or we can maximize the volume of water to be heated or required for particular application.

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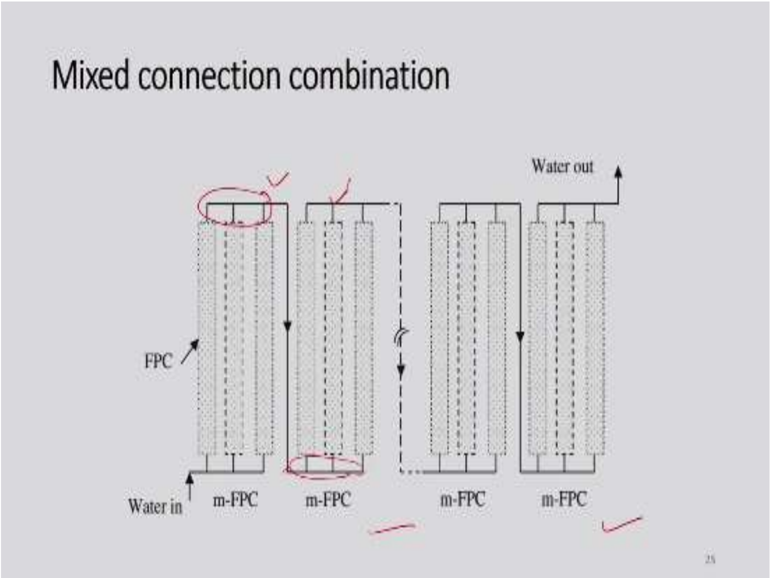

And in case of mixed connections we will have this kind of configurations. These tubes are connected in parallel again these are connected in series. This three are connected in parallel and then these are connected in parallel but know these shapes, this one and this one are connected in series so in order to get the desired temperature and mass flow rate. So this kind of configurations are really applicable in community places like may be hostels or may be in apartments.

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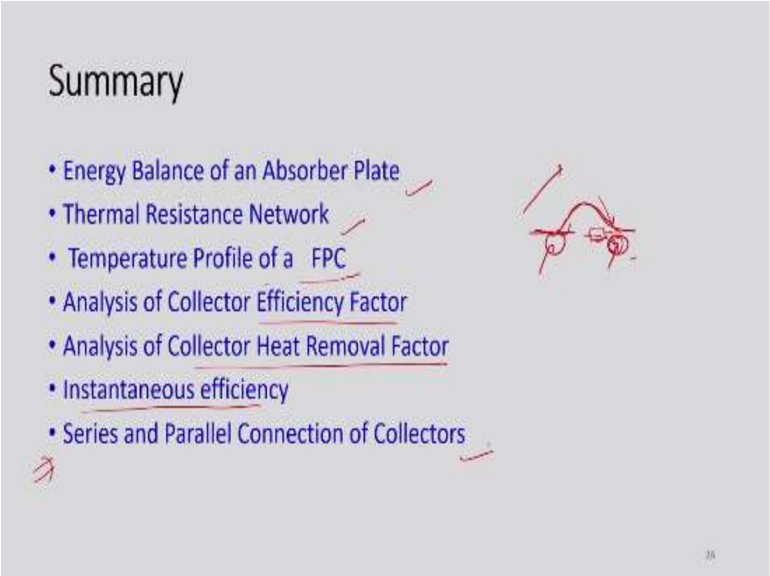

So let us summarize what we have discussed today, we discussed energy balance of an absorber plate then thermal resistance network then temperature profile of a FPC. So what happens in the x direction and y direction. So if we consider two tubes its variation will be something like it varies then it will be something like this. So here heat is carried by the fluid so there is no rise in temperature, but in between this rise will be there and also you have studied how heat is conducted to this tube through conduction as well as the amount of heat received from the solar flux.

So we have analyzed the collector efficiency factor as well as collector heat removal factor and also we have understood the importance of these two factors in designing flat plate collector and also we have studied instantaneous efficiency and collector efficiency. And also we have studied the series and parallel connection of collectors and what condition we can use series connection and what condition we can use it as a parallel connection. Of course we can combine both as per the requirement of amount of volume of water required and particular temperature required. So thank you very much for watching this video. Thank you.