Heat Exchangers: Fundamentals and Design Analysis
Prof. Prasanta Kumar Das
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 40
Surface Condenser (Contd.)

Welcome. If you recall that we are in between solving a problem on Surface Condenser. So, we will without much introduction, we will proceed and let us go to the next slide.

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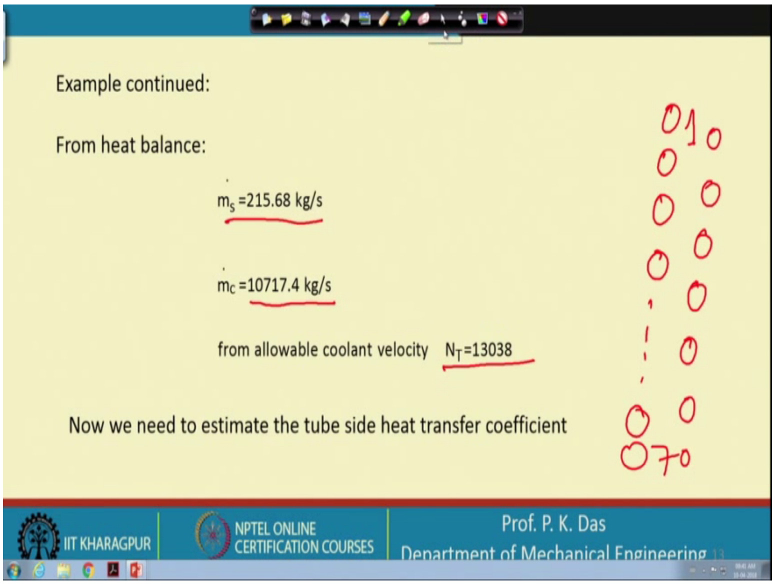

Example continued:

From heat balance:

$\dot{m}_s = 215.68$ kg/s

$\dot{m}_C = 10717.4$ kg/s

from allowable coolant velocity $N_T = 13038$

Now we need to estimate the tube side heat transfer coefficient

So, here you see the example which we are continuing from heat balance, we have got two very important quantities. That is the steam flow rate m dot s. This is one thing we have got and we have got m dot c total heat transfer total rate of heat transfer that also we have got and from the allowable coolant velocity we have got N T that is the total number of tubes. Here we have assumed that on a row, there will be a tube bank, but on a row there will be 70 tubes. So, this is your 70, this is your first tube.

So, there will be tubes like this and we need to know how many tubes will be on a sorry on a column not on a row on a column, how many tubes will be there. So, there will be 70 columns on a column. So, this we have decided and certain thing we have calculated. Now we need to estimate the heat transfer coefficient. So, let us see how we can do it.

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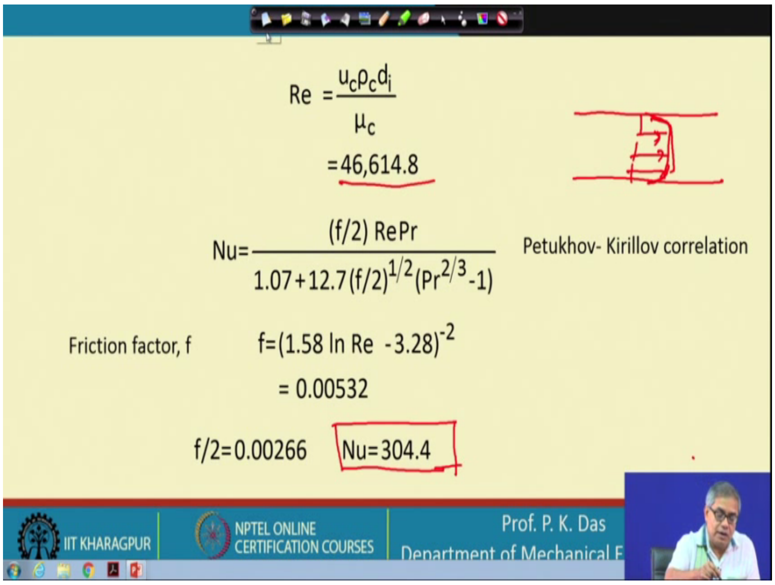

$$Re = \frac{u_c \rho_c d_i}{\mu_c}$$

$$= \underline{46,614.8}$$

$$Nu = \frac{(f/2)\,RePr}{1.07 + 12.7(f/2)^{1/2}(Pr^{2/3} - 1)}$$

Petukhov- Kirillov correlation

Friction factor, f $\quad f = (1.58 \ln Re - 3.28)^{-2}$

$$= 0.00532$$

$f/2 = 0.00266 \quad \boxed{Nu = 304.4}$

Inside heat transfer coefficient, if I have to calculate the inside heat transfer coefficient in the tube.

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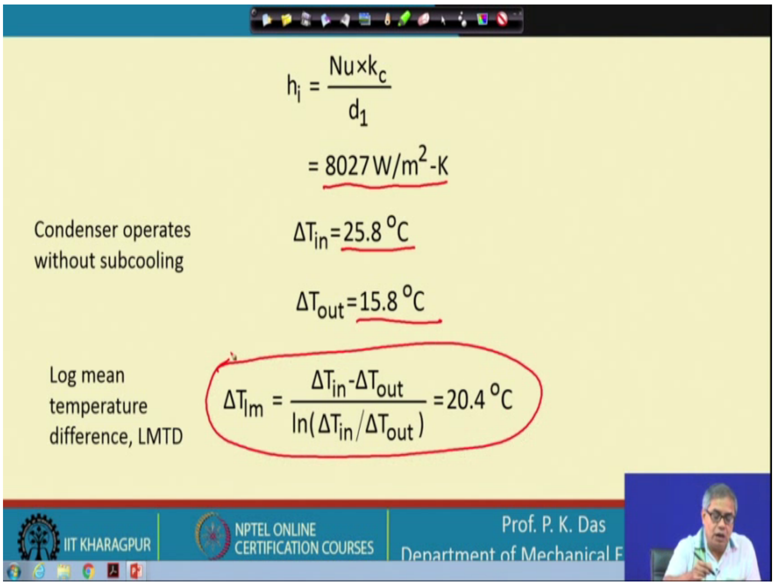

$$h_i = \frac{Nu \times k_c}{d_1}$$

$$= \underline{8027\,W/m^2\text{-}K}$$

Condenser operates without subcooling $\quad \Delta T_{in} = \underline{25.8\,^{o}C}$

$$\Delta T_{out} = \underline{15.8\,^{o}C}$$

Log mean temperature difference, LMTD $\quad \Delta T_{lm} = \frac{\Delta T_{in} - \Delta T_{out}}{\ln(\Delta T_{in}/\Delta T_{out})} = 20.4\,^{o}C$

So, these are the tubes and in the tube we will have some sort of a turbulent flow from the experience one can tell that the coolant flow will be turbulent of course, from Reynolds number. We will get this kind of a thing sorry we have probably gone forward little bit. So, let us go back and then let us try to do it. So, the turbulent flow and it will be given by a heat transfer coefficient where which will be given by Nusselt number

Prandtl number kind of relationship. So, we know the inner diameter we know the fluid property we know the, we have calculated sorry selected a coolant velocity of 2 meter per second.

So, Reynolds number we get again go back. So, Reynolds number we get this our Reynolds number and we use Petukhvo Kirillov kind of correlation. So, from there the Nusselt number we can calculate. This is the nusselt number ok. So, you go through this there is nothing much to explain. So, oh we get the Nusselt number and then we proceed we go to the next slide. So, from the Nusselt number we get the heat transfer coefficient.

So, this is the inside heat transfer coefficient. Now we know the condensing steam temperature. So, in the heat exchanger the inlet side that means, inlet for the coolant. So, inlet side we know what is the temperature difference outlet side we know what is the temperature difference. So, from there we can calculate the log mean temperature difference. So, this our log mean temperature difference, this also we can calculate good; we can move to the next slide.

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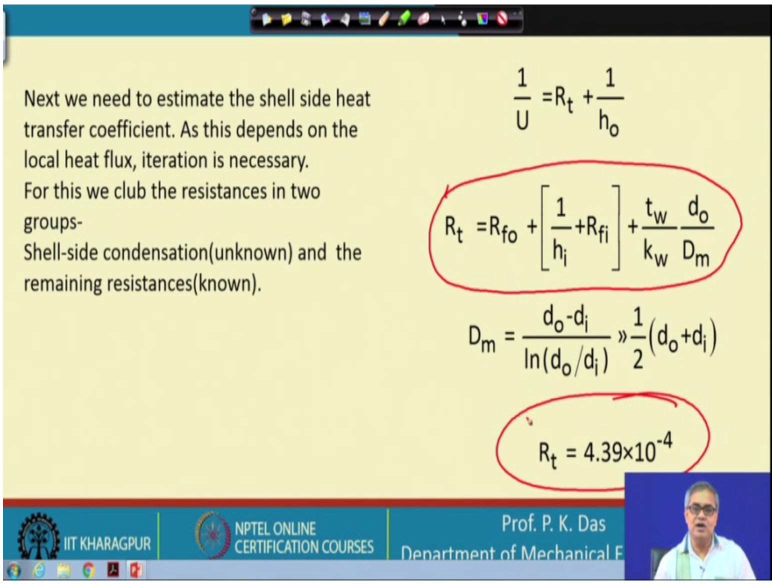

Next we need to estimate the shell side heat transfer coefficient. As this depends on the local heat flux, iteration is necessary.
For this we club the resistances in two groups-
Shell-side condensation(unknown) and the remaining resistances(known).

$$\frac{1}{U} = R_t + \frac{1}{h_o}$$

$$R_t = R_{fo} + \left[\frac{1}{h_i} + R_{fi}\right] + \frac{t_w}{k_w}\frac{d_o}{D_m}$$

$$D_m = \frac{d_o - d_i}{\ln(d_o/d_i)} » \frac{1}{2}(d_o + d_i)$$

$$R_t = 4.39\times10^{-4}$$

So, next slide now we have to calculate the outside heat transfer coefficient. Now if we see let us say this is your sorry let us say, this is your water; let us go to a new page that would be good. So, this is your water.

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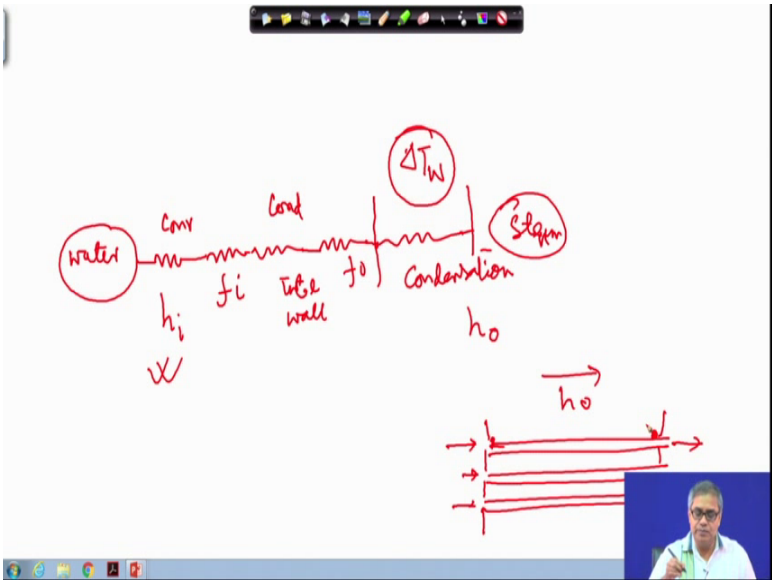

And this is then we have got these resistances. First there will be convection, then there will be inside fouling I am indicating by f i, then there will be conduction due to tube wall tube wall. Then there will be again fouling I am calling it f o and then there will be condensation.

So, very well known thermal circuit and here we will have your steam here we will have your steam. So, water to steam there are 1, 2, 3, 4, 5 resistances, but you see this convective resistance h i we have to calculate and h o you have to calculate; h i calculation already I have described for ho calculation this temperature difference which we will call as delta T w. So, this is this is needed . Nusselt correlation if you go back to Nusselt correlation, you will find that this temperature is needed. Now then locally this temperature has to be determined at each and every point this temperature will be different.

So, at each and every point, then the h o will be different. So, it is a very difficult calculation. What again one should do? One can make some sort of assumption that for a heat exchanger, what we will do? Let us say these are the tubes, sealant tube heat exchanger; let us say this is the tube seat the tubes are connected like this side fluid is entering this side fluid is going out. So, what I mean to say h o will vary along this direction and it is very difficult to calculate h o at each and every point.

So, what we will do, h o we will calculate at this point that is the outside heat transfer coefficient. We will calculate h o at this point and we will take an average. But even for doing this, we have to go for an iterative method. This is very important that even for doing this we have to go for an iterative method and let us see how this iterative method works.

So, next we need to estimate the shell side heat transfer coefficient that is the tube outside convective heat transfer coefficient due to condensation. As this depends on local heat flux, iteration is necessary. For this, we club the resistances in two groups – shell-side condensation which is unknown and which I have told that it is a function of delta T w and the remaining resistances which are known.

So, overall heat transfer coefficient is now one resistance which has clubbed all the different kind of resistances and another resistance it is the condensing resistance on the tube. Then R t will be given by this kind of a formula. So, what are there? Fouling resistance outside, convective resistance of the coolant side, fouling resistance in the tube side and the conduction resistance of the tube and for conduction resistance of the tube, we will use some sort of a mean diameter instead of using the logarithmic relationship for conduction.

So, you will use a mean diameter I mean with the help of computer etcetera, we can even go without taking any kind of approximation or idealization. So, with all these things these are known quantities. Because inside heat transfer coefficient depends on Reynolds number, Prandtl number which are not changing. Because the properties of the liquid we have determined that the average temperature and velocity remains constant. So, R t will get.

So, one component of the total resistance is constant, we have got that and another component is a variable component that we have to determine. So, we are going to determine that.

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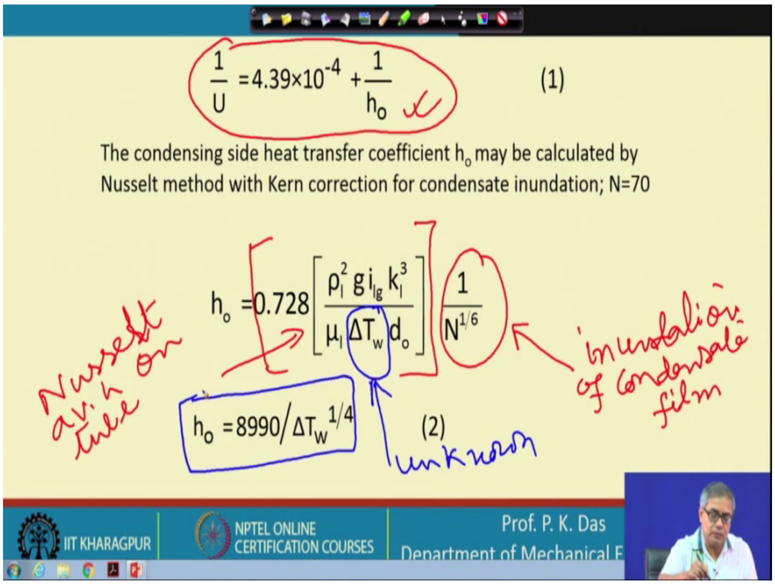

$$\frac{1}{U} = 4.39\times10^{-4} + \frac{1}{h_o} \quad (1)$$

The condensing side heat transfer coefficient h_o may be calculated by Nusselt method with Kern correction for condensate inundation; N=70

$$h_o = 0.728\left[\frac{\rho_l^2 g i_{lg} k_l^3}{\mu_l \Delta T_w d_o}\right]\frac{1}{N^{1/6}}$$

$$\boxed{h_o = 8990/\Delta T_w^{1/4}} \quad (2)$$

Nusselt av. h on tube

inundation of condensate film

unknown

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We get this kind of a formula that overall heat transfer coefficient sorry overall heat transfer coefficient is given by this kind of a formula. Here you see this is unknown and if we can determine this overall heat transfer coefficient we can get. Overall heat transfer coefficient is coming from Nusselt relationship and again the Nusselt relationship has to be modified this is your Nusselt average h on tube. This is due to inundation of condensate film ok.

So, this is Nusselt and that means, this total thing is Nusselt and then this is Nusselt basically and this inundation by condensate film. And here you see that delta T has been delta T w is unknown which is there. So, this is one thing again we have to show which is unknown is this delta T, this is your unknown and N here is 70 already we have assumed. So, ultimately then we get h is equal to this particular equation which is a function of delta T w.

So, let us clean this page. So, this is what we are getting. Now, this is the current scenario and with these let us go to the next slide.

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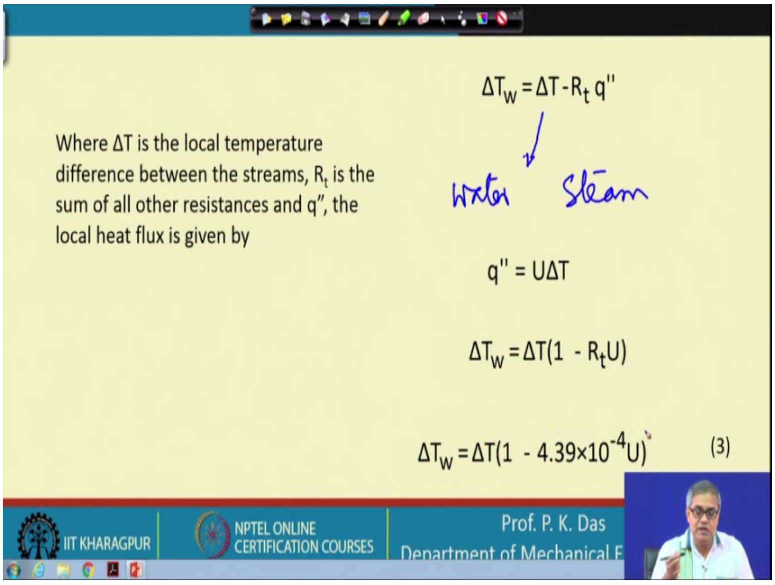

Where ΔT is the local temperature difference between the streams, R_t is the sum of all other resistances and q'', the local heat flux is given by

$$\Delta T_w = \Delta T - R_t q''$$

$$q'' = U\Delta T$$

$$\Delta T_w = \Delta T(1 - R_t U)$$

$$\Delta T_w = \Delta T(1 - 4.39\times10^{-4}U) \qquad (3)$$

So, in the next slide what we try to do is that delta T w as a function of heat flux we have got. This is the delta T is the total heat transfer froms coolant water to steam, what is the sorry total temperature difference.

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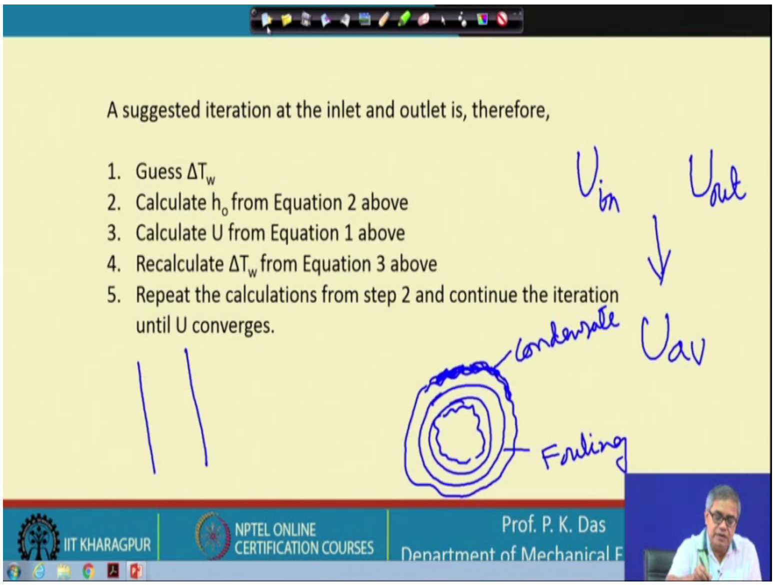

A suggested iteration at the inlet and outlet is, therefore,

1. Guess ΔT_w
2. Calculate h_o from Equation 2 above
3. Calculate U from Equation 1 above
4. Recalculate ΔT_w from Equation 3 above
5. Repeat the calculations from step 2 and continue the iteration until U converges.

So, this is sorry we can go back, let us go back. So, this is from one side is water and another side is steam.

So, this gives the temperature difference between water to steam where delta T is the local temperature difference between the two streams and R t is the sum of all the other resistances q double prime is the local heat flux given by q is equal to q into delta T per unit area of course, delta T w; then we get by this kind of a formula.

And putting all the value of R t, we have calculated; so, we get this kind of an equation. So, this equation we have to use for iteration. A suggested iteration at the inlet and outlet; so, why we have to go for iteration?

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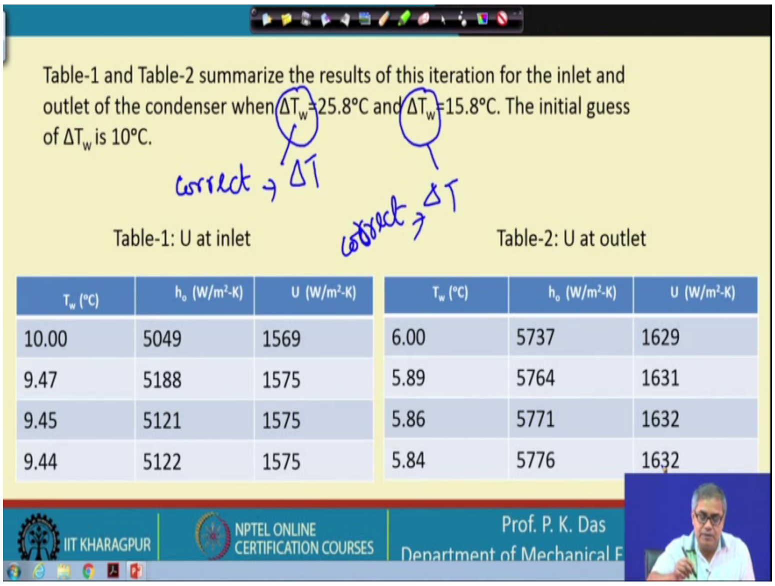

Table-1 and Table-2 summarize the results of this iteration for the inlet and outlet of the condenser when ΔT_w=25.8°C and ΔT_w=15.8°C. The initial guess of ΔT_w is 10°C.

correct → ΔT

correct → ΔT

Table-1: U at inlet

T_w (°C)	h_o (W/m²-K)	U (W/m²-K)
10.00	5049	1569
9.47	5188	1575
9.45	5121	1575
9.44	5122	1575

Table-2: U at outlet

T_w (°C)	h_o (W/m²-K)	U (W/m²-K)
6.00	5737	1629
5.89	5764	1631
5.86	5771	1632
5.84	5776	1632

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Because we have to calculate U, we have to calculate U, we have to calculate U inlet and we have to calculate U outlet and from there we have to calculate U average. So, suggested iteration at the inlet and outlet is therefore, guess delta T w, delta T w we do not know delta T w. What is delta T w? Delta T w you see again it is like this let say inner tube there is a fouling layer which I am showing exaggerated way. Then there is a tube wall and then there is a outer fouling layer fouling; again shown in an exaggerated way and then there is steam condensate. So, then let me draw it with something like this.

So, it is there throughout the tube wall. So, this is your condensate or what we can show this is the tube wall; let me clear it then show it.

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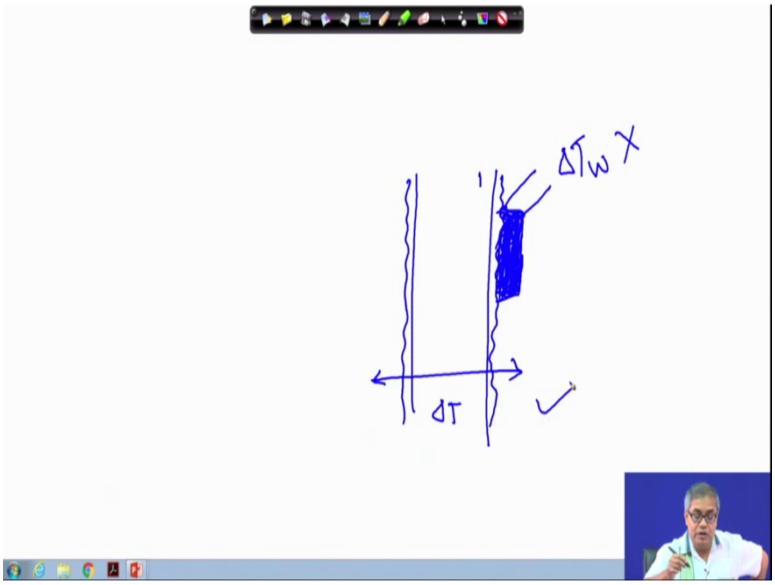

So, basically it is like this; there is an inner fouling wall, there is an outer fouling layer and there is a condensate layer. Let us say this is your condensate layer, exaggerated way for your understanding only I am drawing this and this temperature difference is your delta T w ok. So, this is again these temperature and there is another. So, this is your delta T. So, delta T w and delta T we have to understand.

So, this is your delta T w and this is your delta T. This is not known, this is not known. This we have got some idea. With this, let us go back to our previous slide. A suggested iteration at the inlet and outlet is therefore, guess delta T w calculate ho from equation 2 above. We have 3 equations, we have noted as 1, 2 and 3. Let me go back and show these equations that will be important for tube.

So, this is your equation 3, this is your equation 1 and this is your equation 2. So, equation 1, 2 and three are very important. So, let us go back. So, calculate ho from equation 2 above calculate U from equation 1 above and recalculate delta T w from equation 3above repeat the calculation from step two and continue the iteration T u converges. So, this is what we have to do this is what we have to do and then. Let us go back sorry let us go forward move forward.

And then in the next slide table 1 and table 2 summarizes for the inlet and outlet of the condenser where delta T w just a minute here I can see there is a mistake this delta T w should be delta T and this delta T w should be delta T. So, this is the inner I am writing it correct. It should be this should also be corrected this should be delta T.

So, this delta T as I have mentioned. So, this is the difference between temperature difference between the two streams. So, at the inlet it is 25.8 degree Celsius and at the outlet it is 15.8 degree Celsius. And for the inlet let us say the initial guess of delta T w is 10 degree Celsius. So, you see this table. So, we have assumed 10 degree Celsius from there we get a heat transfer coefficient outside heat transfer coefficient of 5049 over all heat transfer coefficient of U. I will do the equation three we solve we get 9.47 and then again we land up with some overall heat transfer coefficient 15 75 that means, 1005 and 75.

And we continue this we get ultimately 9.44 degree Celsius is delta T w at the inlet. Similarly we assume 6 degree Celsius as delta T w at the outlet we do the same kind of iteration and ultimately we get the ultimately we get the heat transfer coefficient overall heat transfer coefficient as 1632.

So, again let me tell you what we are up to please note the corrections the these delta T w should be delta T this delta T w should be delta T they are at the inlet and at the outlet the temperature difference between this streams.

So, with all this things what we do we try to calculate the overall heat transfer coefficient at the inlet and outlet. Knowing the overall heat transfer coefficient at the inlet and outlet, we calculate the average overall heat transfer coefficient for the entire tube length and then we proceed with our calculation.

So, next slide let us see.

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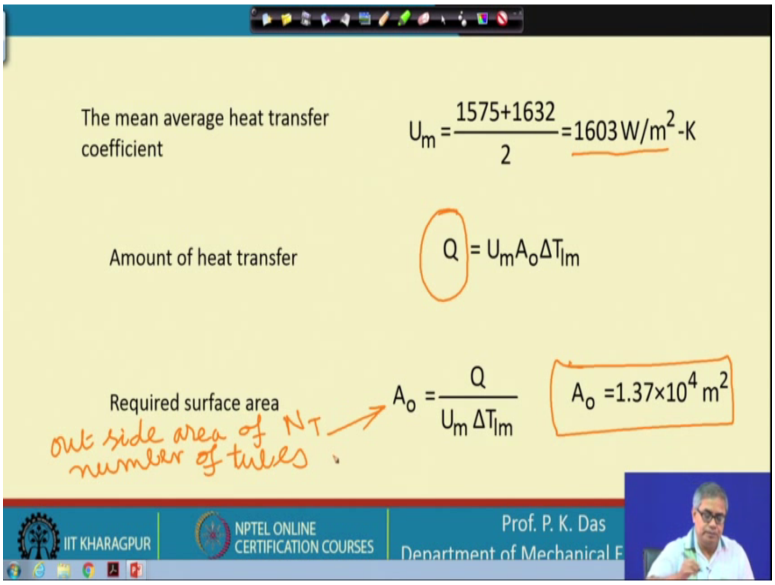

The mean average heat transfer coefficient $U_m = \frac{1575+1632}{2} = \underline{1603\,W/m^2\text{-}K}$

Amount of heat transfer $\boxed{Q} = U_m A_o \Delta T_{lm}$

Required surface area $A_o = \frac{Q}{U_m \Delta T_{lm}}$ $\boxed{A_o = 1.37\times10^4\,m^2}$

out side area of N_T number of tubes.

So, from the previous page we have taken these two values. Again let me go back to the previous page. So, that you can see once again; so, inlet side heat transfer coefficient we have got 1575 watt per meter square Kelvin and outlet side heat transfer coefficient we have got 1632 watt per meter square Kelvin. So, we these two we calculate the average heat transfer coefficient.

So, average heat transfer coefficient is this one. Average heat transfer coefficient is this one. Amount of heat transfer; now we can calculate the amount of heat transfer which is known which is known because how do I know we have already calculated it if you recall it the we know how much steam we have to condense and bring it to the saturated liquid condition. Then we know that steam at what condition it is entering the condenser. So, from there we know q.

So, q we know average heat transfer coefficient we know logarithmic temperature difference we know and then only unknown that is their that is A o because average heat transfer coefficient has been calculated based on outside area of the tube and A o we can calculate.

So, this is the value of A o. So, this much outside area of the tubes is needed let me write it. So, outside area of N t is tube number also we have calculated number of tubes. So, this we have got and outside tube diameter also we know. So, if we know outside tube diameter, then we can calculate the tube length needed to get this outside area of the tube let us clean it and let us go back to the next slide.

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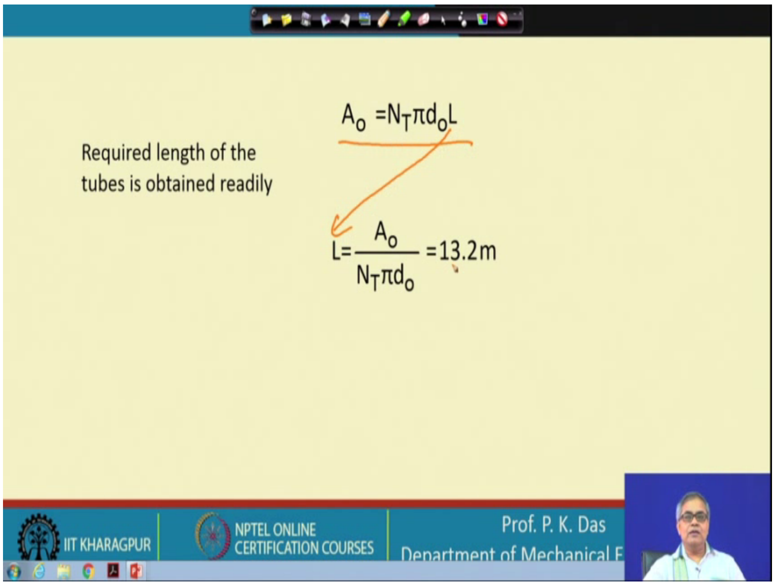

Required length of the tubes is obtained readily

$$A_o = N_T \pi d_o L$$

$$L = \frac{A_o}{N_T \pi d_o} = 13.2\text{m}$$

So, a 0 equal to N t pi d 0 into L is the only unknown and from here we can calculate L. So, L is 13.2 meter. So, this is the tube length each of the tube is of this length and we have to have this much length of the tube for getting the condensation which we are aiming at in this surface condensation. So, this is the end not the end of the problem there are many things to be discussed to be appreciated. So, I will just cursorily very briefly I will recapitulate what we have done. May be next day when we will again start with this problem we will repeat the same thing, but at the end you should understand how we have done the design.

So, basically the steam conditions have been given certain minimum condition that means, coolant inlet temperature coolant outlet temperature that is that has been given and we have assumed a few thing inner diameter of the tube outer diameter of the tube all the material properties because materials tube materials we have assumed. And steam and water property and then what we have got we got certain basic quantities of the heat exchanger one is total rate of heat transfer another is the steam flow rate another is the water flow rate. With these things and we have also assumed or taken as design data what should be the velocity of water through the tube.

So, from there we have got the number of tubes. Again we have made an assumption that there will be a tube bank and in the tube bank on a column there will be 70 number of tubes.

So, then we could calculate the inside heat transfer coefficient readily, but outside heat transfer coefficient we have to calculate knowing the some sort of a temperature difference for which iteration is needed. And we have gone for iteration. And ultimately we have determined the outside heat transfer coefficient average outright outside heat transfer coefficient average overall heat transfer coefficient and with all this things then we are able to calculate the outside area of all the tubes or cumulative outside area of the tubes needed to condense the amount of steam which we need to condense. So, then from there we could calculate the number of tubes already we have calculated. Now we can calculate the length of the tubes. Now probably we can check whether the pressure drop is all right or not. Now we can have some idea what could be the cell diameter. Now we can go for some sort of iteration or some sort of exploration if we select other kind of velocity what will be the effect on the design of the heat exchanger. So, all these exercise we can do. So, with this I with this note I end here, but the problem discussion on this problem does not end here. We like to take the benefit of a problem which is bit comprehensive which is bit I mean more or less a practical problem to understand other aspects of surface condenser when it is having sealant tube kind of a configuration.

Thank you.