Process Equipment Design
Prof. Shabina Khanam
Department of Chemical Engineering
Indian Institute of Technology – Roorkee

Lecture –38
Design of Evaporator-5

Hello everyone. I welcome you all in 38th lecture of the course Process Equipment Design and here we are going to design the evaporator. If you remember last two lectures there we have discussed design of evaporator and solve the set of nonlinear equations with the help of Badger McCabe method as well as Newton-Raphson method. And in this lecture, we are going to illustrate the design of evaporator with the help of examples. So, let us focus on example 1.

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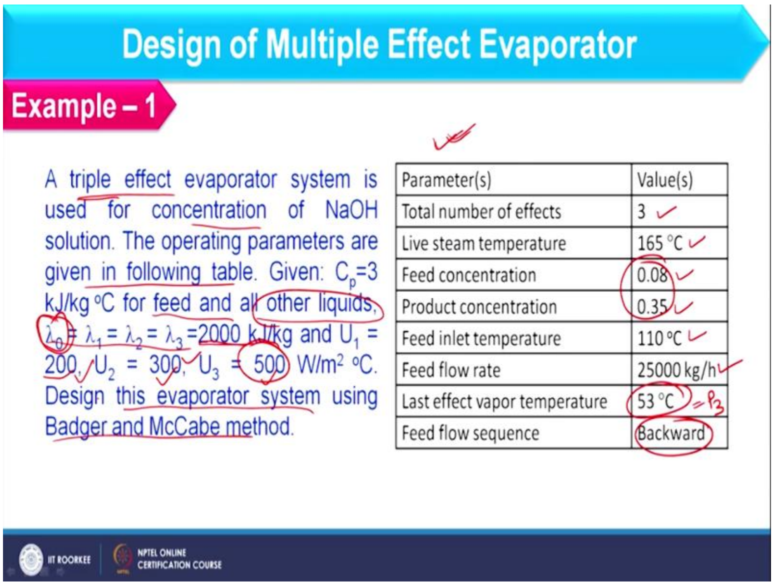

And in this example a triple effect evaporator system is used to concentrate sodium hydroxide solution, operating parameters are given in the table which is shown over here that we will discuss later on. In this case Cp of all feed as well as liquid streams are given as 3 kilojoule per kg degree Celsius. And latent heat of vapourization in each effect that is first, second and third effect along with the steam we are considering that as 2,000 kilojoule per kg.

U 1 is given as 200, U 2 300 and U 3 500. So, we have to design this evaporator system with the help of Badger McCabe method. So, let us see the parameters. We are given number of effects as 3, steam temperature as 165 degree Celsius, feed concentration 8% by weight and product concentration 35% by weight. So, we have to design the triple effect evaporator system to concentrate the feed from 8% to 35%.

Feed inlet temperature is 110, feed flow rate 25,000 and last effect vapour temperature is equal to 53 degree Celsius or you may be given here the pressure that is P 3 because last effect is connected with the vacuum pump and that value is known to you. So, as far as feed flow sequence is concerned it is consider as backward. And if you focus on this backward sequence feed should enter from the last effect then to second effect and then to first effect.

So, if we focus on overall heat transfer coefficient you see the last effect overall heat transfer coefficient has maximum value and it keeps on decreasing when we move from last effect to first effect and the reason is very simple. When the feed is entering into the last effect it is having highest flow rate and when it enters into the second effect some amount from this feed is converted into the vapour.

So, whatever liquid is entering into second effect it is having less flow rate as compared to the feed and so the case is there for first effect. So, in this way U 1, U 2, U 3 will vary as per the sequence. If we move on forward sequence then U 1 will be maximum for first effect and so keep on decreasing till last effect.

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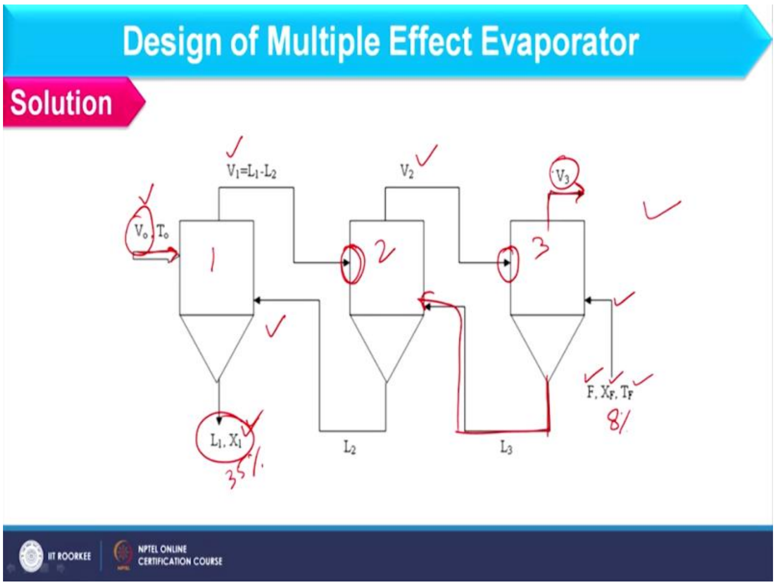

So, let us start the solution of this example here we are having the schematic where first, second and third effects are shown and feed enters into third effect because it is backward sequence with the flow rate F concentration XF and at temperature TF. So, when vapourization takes place V 3 exits from the top L 3 which is exiting from the bottom is entering into the second effect as it is shown over here and so L 2.

And finally we are having the product from first effect and that is L 1 and X 1. So, if you consider XF is available at 8% and final product that is the X 1 value is given as 35%. So, in this way concentrations are known to you and as far as vapour movement is concerned feed will enter into the first effect because movement of vapour will be independent to the movement of feed.

Vapour as well as steam movement will always be in forward direction. So V 1 enters to first effect V 1 generated which is used as a heating media in second effect. V 2 is generated which is used as a heating media in third effect and so V 3 will be generated. So, in this way I hope sequence is clear to you, so let us focus on the solution of it. The first step will be to derive governing equations because whatever equations we have derived in previous lectures these are basically for forward sequence.

And as the sequence changes these governing equations will also change. So, let us derive the equation first.

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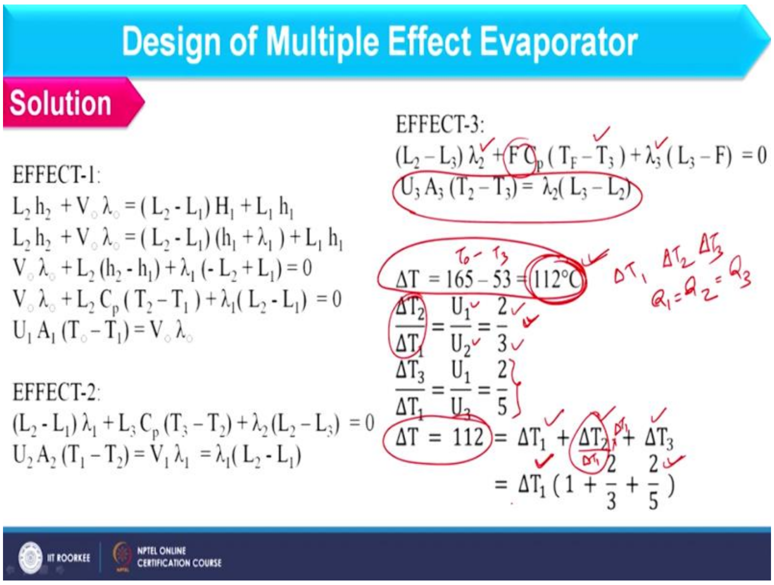

So, let me first focus on the effect 1 and if you see this is basically the schematic of it and we are focusing on first effect and when we consider the first effect whatever stream is exiting, whatever stream is entering like V 0 and L 2 and the stream which are exiting like V 1 as well as L 1 all these we have to consider because we have to make the material energy balance and for that we basically make an envelope around the system.

And whatever streams are entering into it and exiting from it that we have to focus on. So, as I am having two stream which are entering and two stream which are exiting. So, let us see the material and energy balance. So, if we focus on the enthalpy balance first of all we consider whatever streams are entering into this that is the first effect. So, I am having L 2 so L 2 contains enthalpy h 2 that is the enthalpy of the liquid.

And next is I am having V 0 which is entering so V 0 will transfer lambda 0 heat to the system and that will be equal to V 1 capital H 1. So, when we make the balance for V 1 that should be nothing, but L 2 – L 1 so I am considering L 2 – L 1 capital H 1 because that is the enthalpy of the vapour and similarly I am considering L 1 which contains enthalpy h 1. So, let us elaborate that.

Further, I am having L 2 h 2 + V 0 lambda 0. And next I am having L 2 – L 1 and we can further elaborate this capital H 1 which is basically small h 1 + lambda 1 and that is basically the enthalpy of vapour which is equal to enthalpy of liquid plus heat of vapourization and that again add the term L 1 containing h 1 enthalpy. So, let me rearrange all these and we can find the equation like V 0 lambda 0 + L 2 h 2 – h 1.

So h 2 will come from here and h 1 will come from here when we consider this. Further, we will add another term and that will be lambda 1. Lambda 1 basically includes L 2 and L 1 like – L 2 + L 1 and that should be equal to 0. Further, convergence of enthalpy into Cp T we can find this as enthalpy balance that should be V 0 lambda 0 + L 2 Cp T 2 – T 1 we can expand this term and then plus lambda 1 bracket L 2 – L 1.

So, here I am having another term that is lambda 1 and this should be L 1 – L 2. In this way we can consider the enthalpy balance and finally we have the rate equation for first effect and that should be U 1 A 1 bracket T 0 – T 1 that should be equal to V 0 lambda 0. Right now I am considering this as A 1, but we assume that each effect consists same area. So, finally we will consider that as A.

In the similar line I can derive the equation for effect 2, but as I have derive equation for first effect I can simply expand that to effect number 2 and for this here I should consider V 1. So, that V 1 is nothing, but L 2 – L 1 as you can see over here. So, L 2 – L 1 lambda 1 + L 3 Cp T 3 – T 2 because L 3 is the feed to this and similarly I am having lambda 2 L 2 – L 3 and that should be equal to 0.

And this is the rate equation where I have to consider L 2 – L 1 at the place of V 1. So, in this way we can consider equation for second effect and similarly we can consider equation for third effect as L 2 – L 3 into lambda 2 + F Cp TF – T 3 because here we have the feed and similarly lambda L 3 – F should be considered and this is the rate equation. So, in this way we can derive the governing equation of all three effects.

And now will start the solution of these equation using Badger McCabe method. So, the first step of this method is to decide the unknown temperature of this system. Now, as far as unknown temperatures are concerned for T 1, T 2 and T 3 we usually know T 3 and that is given as 53 degree Celsius in this problem and T 1 and T 2 are unknown to me. So, we can consider equal heat transfer in each effect and so we can consider temperature differences.

So, let us see the solution of that step. To find out temperature difference of each effect we should consider total driving force which is available in the system and that should be T 0 – T 3. So 165 – 53 we can consider as 112 and this 112 degree Celsius is distributed as delta T 1 delta T 2 and delta T 3. So, considering equal heat transfer in each effect that is Q 1 should be equal to Q 2 should be equal to Q 3.

We can find delta T 2 / delta T 1 which should be equal to U 1 / U 2 considering equal area of each effect U 1 and U 2 values are known to you so you can consider 2 / 3 and similarly delta T 3 / delta T 1 should be 2 / 5. So, when I consider total driving force that should be equal to delta T 1 + delta T 2 + delta T 3. And further we can consider this as a division of delta T 1 into multiplication of delta T 1.

So, this value is usually known to me and that I consider as 2 / 3 and similarly 2 / 5. So, solving this equation we can find out delta T 1 value.

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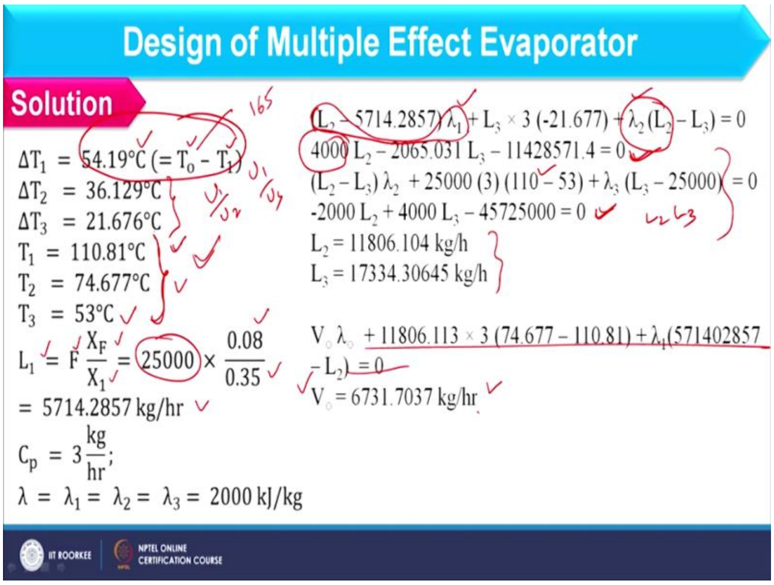

And so delta T 1 you can obtain as 54.19 degree Celsius and that should be equal to T 0 – T 1. Similarly delta T 2 and delta T 3 we can find out because I know delta T 1 and I know U ratios U 1 and U 2 or U 3 or U 1 / U 3. So, in this way I can find temperature of each effect. So, T 1 I can consider using this equation where T 0 is available at 165. So, considering this T 1 should come as 110.81 T 2 74.677 Celsius and T 3 will be 53.

When you consider the temperature as well as temperature difference whatever you have calculated last effect temperature may vary and variation is very little like 53 point something, but last effect temperature is fixed quantity that you cannot play with. So, that should always be the given temperature and that should be 53 in this particular example. Now once I know the unknown temperature of effects that is T 1, T 2 and T 3 we should find out the flow rates L 1, L 2 and L 3 and so the V 0. So, let us see how to find it.

Now if you focus on this example this is basically the backward sequence and when we consider the product flow rate and product in this case is the L 1. So, when we consider the product flow rate we assume that vapour consist zero solute. So, whatever solute is available in the feed the whole solute is available in the product now. So, we can make the component balance such as F XF should be equal to L 1 and X 1.

So, here you know F X 1 as well as X 2. So, here you know F XF as well as X 1. So, here we can consider L 1 X 1 should be equal to F XF and that should be equal to 25,000 into 8% / 35% by weight. So, here we can find out L 1 as 5714.2857 kg per hour. Next step is to find out L 2 and L 3. So, to do that let us focus on the governing equation again. So, here I am having the governing equation when I focus on effect number 2 as well as effect number 3 and enthalpy balance of these effects.

So, if you focus on this particular equation we can consider that here I am having L 1, L 2 where L 1 is known to me L 2 is unknown to me. Similarly, here I am having L 3 which is unknown to me. So L 2 and L 3 are unknown to me in this term as well. And similarly when I focus on effect number 3 L 2 and L 3 are unknown to me, feed is known to me and L 3 is unknown to me.

So, what is the meaning of this if I consider these two equations of enthalpy balance of effect number 2 and 3 I can say that the only unknowns are L 2 and L 3. So, here I am having two unknowns and two equations. So, unique solution will exist which you can solve simultaneously because once I know the temperature these equations become linear in nature. So, you can solve these simultaneously and while solving this you have to put the known parameters so let us see that. So, here I am having L 2 – L 1. So L 1 value I know now.

Lambda 1 I already know L 3 is unknown to me and so you can consider temperature difference and which you have already calculated previously. Similarly, lambda 2 is known to me and L 2 and L 3 are unknown to me. So, when you resolve these equation you can find the equation as 4,000 L 2 because here you are considering lambda 2 L 2 and here we are having lambda 1 and L 2.

Lambda 1 and lambda 2 values are equal so it is simply added and that gives 4,000 L 2. Similarly, you can find out other term so in this way you can find out the equation of second effect. In the similar line, you can find out the equation for third effect putting all values where feed temperature is given as 110. So, in this way you can have these two equation and unknowns are L 2 as well as L 3 you can solve these equations simultaneously.

And find the value of L 2 as 11806.104 kg per hour and L 3 as 17334.306 kg per hour. So, once you have L 2 and L 3 values you can find out V 0 values considering enthalpy balance of first effect where the term V 0 is available alone. So, in that case you can find out V 0 by solving this equations because all known parameters are with you. So, value of V 0 you can find as 6731.7037 kg per hour.

Now what is next step? When I know the temperatures of first and second effect I know the flow rates of all effects along with the steam flow rate. What is next? We should find out area of each effect. So, for that we will use the rate equation of each effect so let us focus on that.

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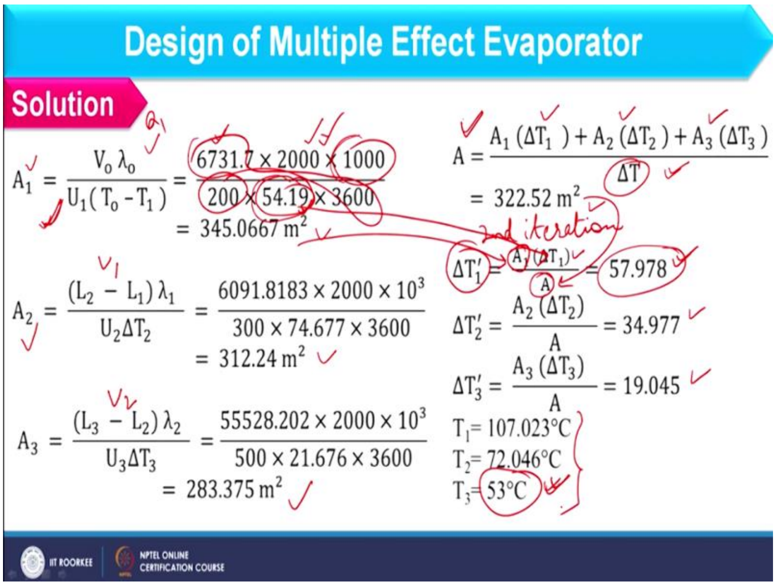

Here I am having area A 1 for first effect and that should be equal to V 0 lambda 0 that is basically the Q 1 divided by U 1 T 0 – T 1. So, you know all parameters V 0 should be given as kg per second when I am considering this balance. So, here it should be considered in seconds and lambda 0 is given as 2,000 and 1,000 because this is available in kilojoule and 200 is the U 1 value which is available in watt per meter square degree Celsius.

54.19 is the temperature difference and so you can find out area of first effect as 345.07 meter square. In similar line you can find out A 2 as 312.24 meter square and so A 3 which is coming out as 283.375. So, here basically you should consider V 1 and here you should consider V 2. Now, once I am having area of each effect and initially we have assumed that area of each effect should be equal.

So, we have to find out average area and then we will consider that how the area of each effect is deviating from the average area and so we will revise the temperature difference values. So, let us see how to find out average area in the system. So, that you can find out considering this equation where A = A 1 delta T 1 + A 2 delta T 2 + A 3 delta T 3 and it should be equal to A delta T.

So, average area we can find as 322.52 and you should consider here that average area is basically on temperature difference weight. So, we can find out revise temperature difference as delta T 1 dash and from here onwards we have second iteration. So, delta T 1 dash should be equal to A 1 delta T 1 / A. How much area is deviating from the average area. So, A 1 is this temperature difference in first effect is this and area is this.

So you can find out temperature difference in first effect that is the revised value and which should be equal to 57.978. So, you can consider deviation in two iteration. In first iteration it is 54.19 in second iteration it is 57.978. So, sufficient deviation is there. Similarly delta T 2 dash and delta T 3 dash you can find out and so temperature of each effect. Last effect temperature will always be fixed at the given temperature and that is 53 in this example.

So, now you have to repeat all steps considering these T 1, T 2 and T 3 values and next you have to find out L 1, L 2, L 3 and so V 0 and so the area A 1, A 2, A 3 and so the average area and further you have to see whether deviation is there or not.

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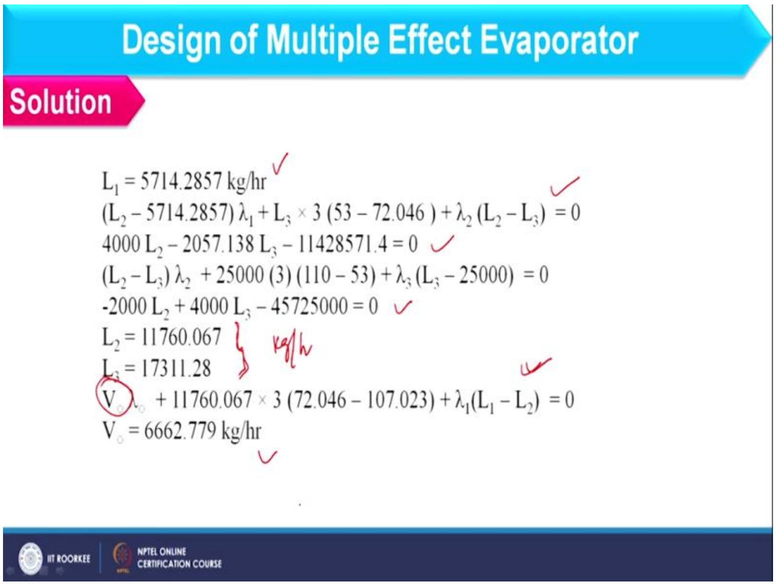

So, let us see that quickly. L 1 is known to me and these are basically enthalpy balance of second and third effect and values you can find as we have discussed in previous iteration and so you can find out L 2 as 11760.067 and 17311.28 kg per hour. So, further considering enthalpy balance of first effect you can find out value of V 0 which is coming out as 6662.779 kg per hour.

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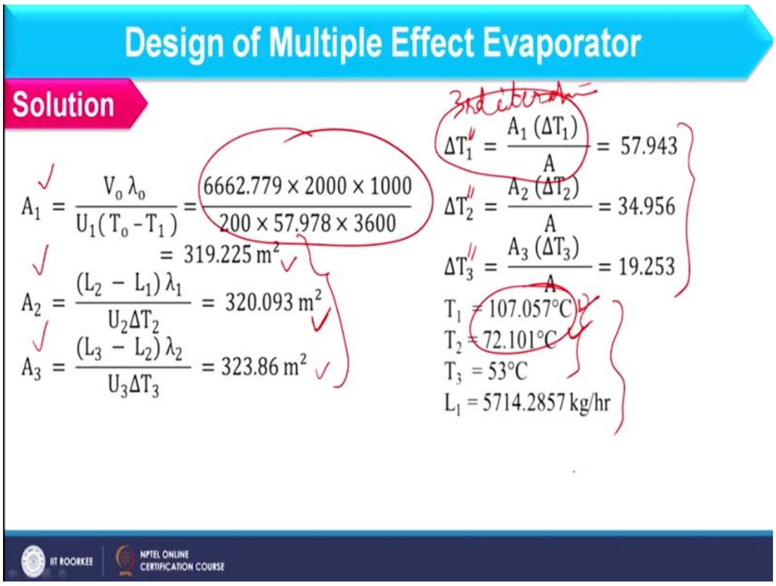

And so you can find out area of each effect. So, now the area of each effect considering all these value I am not going into details of this because this point we have already discussed in the last iteration. So, A 1 value you can obtain as 319.225 A 2 320.093, A 3 323.86 and so you can find out that these areas are different. So, next we have to find out average area and considering these average area as well as the calculated area you can find out delta T 1 prime.

You can find out delta T 1 double prime and delta T 2 double prime and delta T 3 double prime because from here I am having the third iteration. So, you can find these values as so T 1, T 2, T 3 as these. So, if you focus on T 1, T 2 values and compare with the last iteration these values are pretty close to the value which you have considered in last iteration and similarly you have to carry out all iterations.

So, maybe next iteration will give the two consecutive value equal and so that will be the final solution of this problem. So, I am not going into detail of this assuming that you can do on your own.

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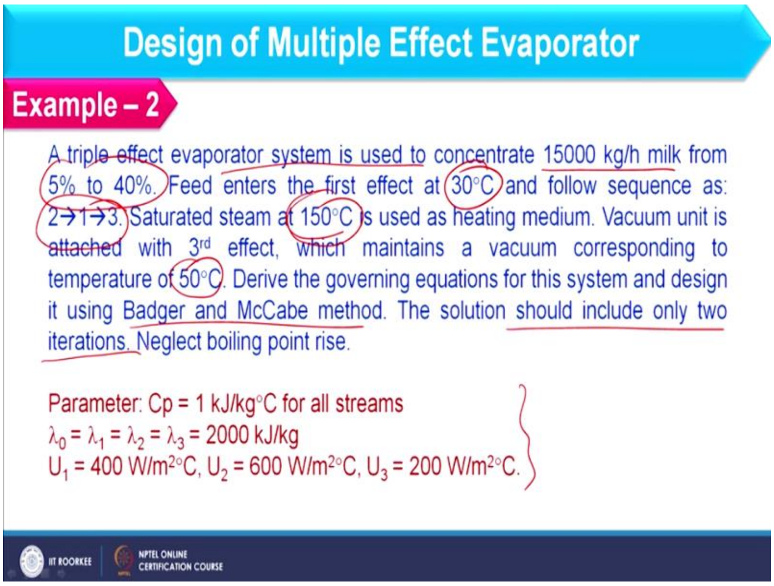

So, I am having second example also which I will cover quickly because here I am having different flow sequence. So, here again I have to design a triple effect evaporator system to concentrate 15,000 kg per hour of milk from 5% to 40% flow sequence is 213 that is basically the mixed. Feed enters at 30 degree Celsius, saturated steam is available at 150 and last effect temperature is 50.

So, total 100 driving force is there in the whole system and we have to design this using Badger McCabe method and here I am having some known parameters. So, in this solution we have to consider only two iteration neglecting boiling point rise.

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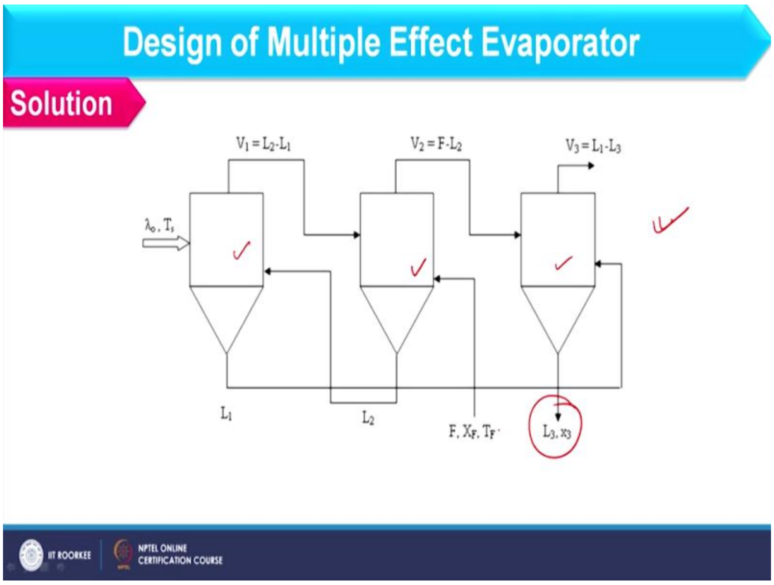

This is the flow sequence where feed is entering into second effect then to first effect and then to last effect. So, in this way final product exits from the last effect and that is L 3. So, usually XF and X 3 are known to you.

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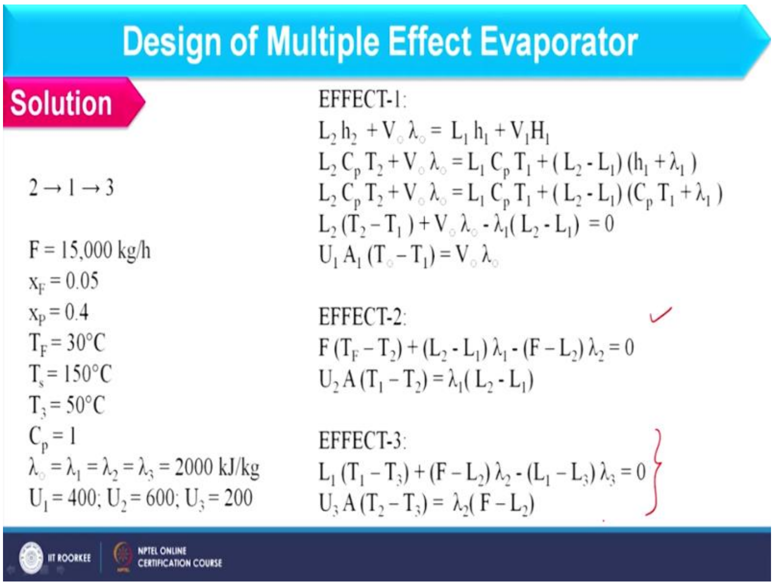

And let us see the governing equations of this. So, here I am having sequence as 213 this is the schematic for first effect you can simply consider L 2 h 2 because it is entering V 0 lambda 1 as we consider previously and L 1 h 1 and so V 1 capital H 1. So, in this way balance you have to carry out for energy as well as mass and you can resolve the final equation as L 2 T 2 – T 1 + V 0 lambda 0 – lambda 1 L 2 – L 1.

And so this is the rate equation U 1 A 1 T 0 – T 1 = lambda 0 V 0. Similarly, you can find out enthalpy balance and rate equation for second effect and so for third effect.

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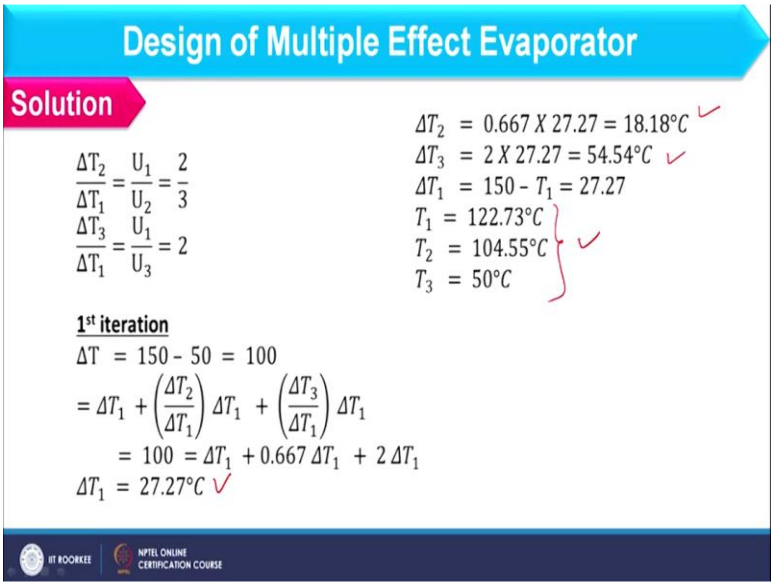

So, let us quickly cover the solution of this. We again have to find out temperature of each effect T 3 temperature is known to you. So, let us see the temperature of first and second effect considering equal heat transfer in each effect as we have discussed in previous example. So, I am not going into detail of that just see how the value can be obtained. So delta T 1 we can obtain as 27.27 degree Celsius delta 2 18.18 and delta 3 54.54. So T 1, T 2 and T 3 you can find accordingly as these.

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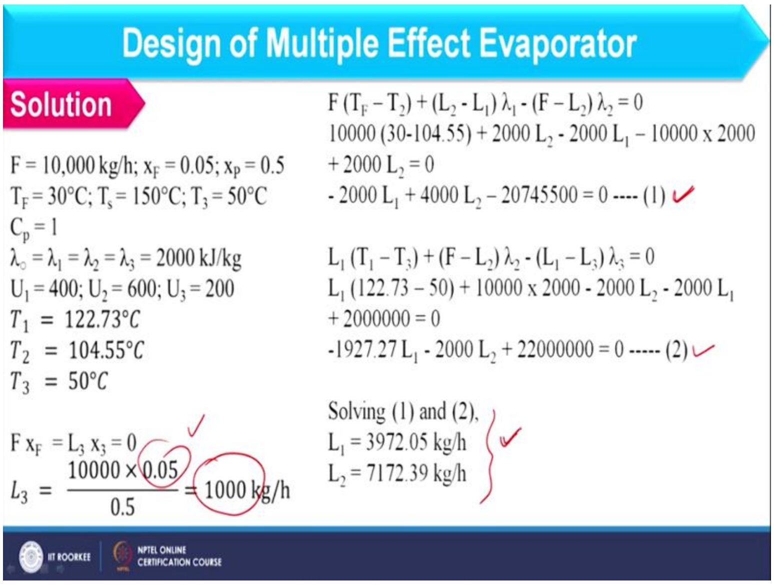

As product is exiting from the last effect you can find out L 3 as 10,000 into 0.05 divided by 0.5 because 5% to 50% is total concentration of feed is considered in this example. Let us further we will focus on L 1 and L 2 calculation as we have discussed in the previous example. So, here I am having two equation which you have to solve simultaneously and value of L 1 and L 2 you can obtain as given here.

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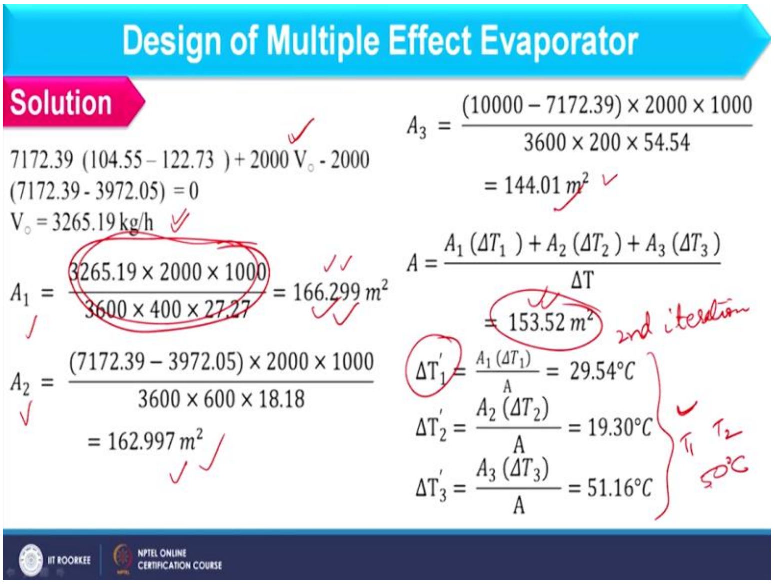

And so we can find out the steam flow rate that is 3265.19 considering the enthalpy balance of first effect and now we can find out area of each effect. So, area of first effect you can simply find out based on rate equation which comes out as 166.299 A 2 you can find out as 162.997 and so you can find out A 3 as 144.01 average area you can find as 153.52 from here you can see the deviation and so we require second iteration.

So, revised temperature differences of each effect you can find considering average area as well as the actual area and you can find the value as these. And once I am having these value you can find out T 1, T 2 and T 3 is fixed at 50 degree Celsius.

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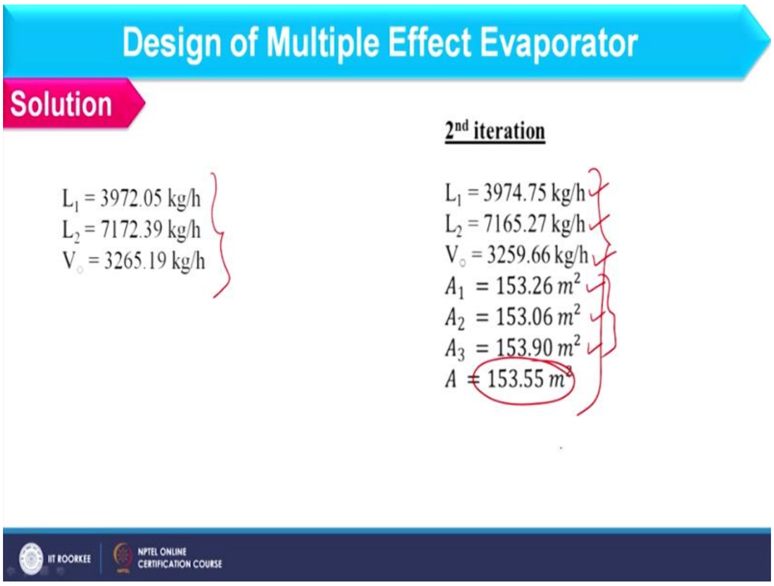

And so the result of second iteration you can compile as L 1 3974.75 L 2 7165.27 V 0 3259.66 A 1 that is area of first effect as 153.26 A 2 153.06 and A 3 153.9 and when you average it the average is pretty close to these value and that is 153.55, but still solution is not completed you have to iterate further. Till all six parameters of two consecutive iteration should be equal. So, in this way we can design triple effect evaporator system.

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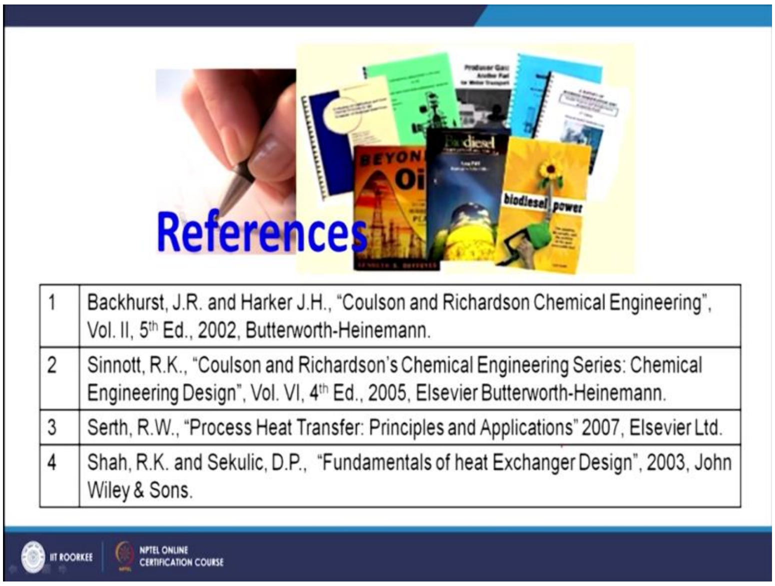

And here you can find the references.

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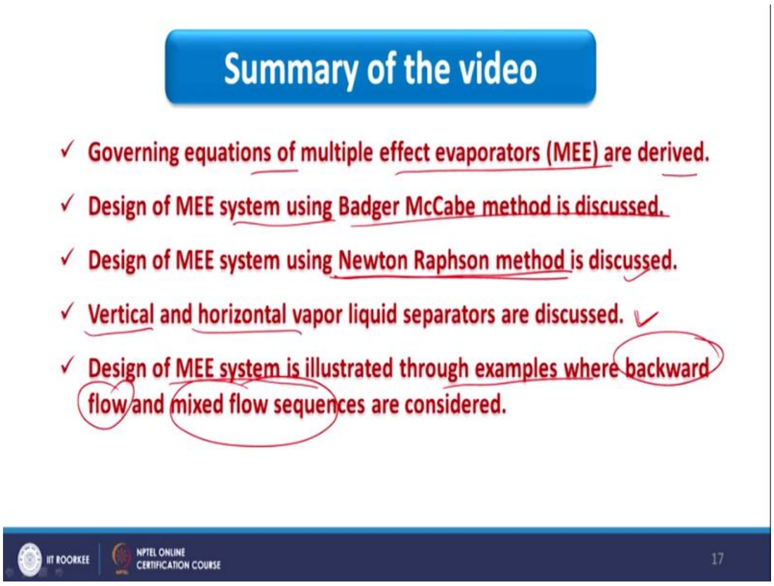

And now we have to summarize the video. So, this summary includes the summary of the lectures 1, 2 and 3 of this week and it goes as in these lectures governing equation for multiple effect evaporator system are derived. Design of multiple effect evaporator system using Badger McCabe method we have discussed and further we have considered design of multiple effect evaporator system using Newton-Raphson method.

We also focused on vapour liquid separator whether it is placed vertically or horizontally and finally we have considered design of multiple effect evaporator system using two examples where backward sequence as well as mixed flow sequence are considered and forward sequence we have already considered when we have design the triple effect evaporator system and where we have focused on derivation of each governing equation. So, that is all for now. Thank you.