Process Equipment Design

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Lecture –36
Design of Evaporator-3

Hello everyone. I welcome you all in the 8th week of the course Process Equipment Design and here we are in 36th lecture of this course and in this lecture we will discuss design of evaporator. And if you remember this topic we have already started in 7th week where 34th and 35th lectures are devoted to this and we are continuing the design of evaporator in 8th week also. So, let us start the design of evaporator.

If you remember the 35th lecture there we have discussed the multiple effect evaporator functioning as well as different points which are related to triple effect evaporator in every detail. However, we have not derived the governing equation which are related to multiple effect evaporator and especially triple effect evaporator. So, in this lecture we are going to derive the governing equation. We will solve this equation to design triple effect evaporator.

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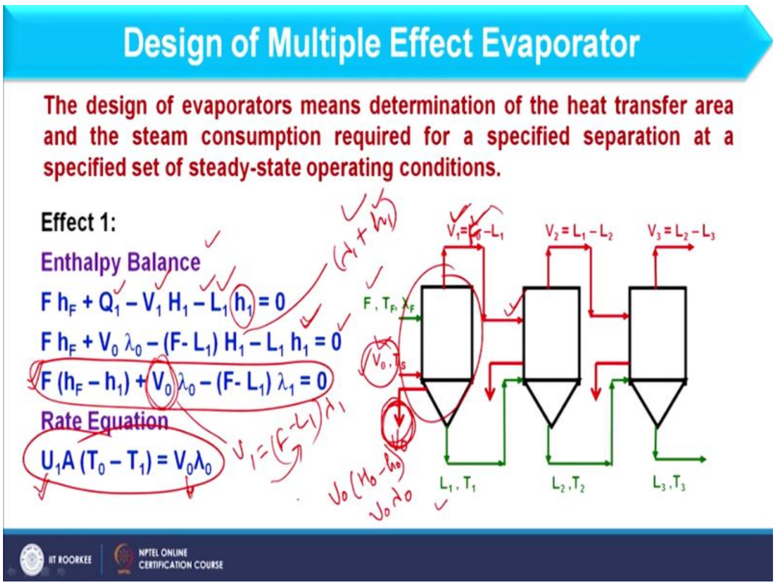

So, as far as triple effect evaporator is concerned this is the schematic where feed is entering into the first effect and concentrated liquor is entering from first to second effect and then to third effect and finally we have concentrated product from third effect. And similarly we can have the movement of vapour where steam is entering into the first effect and vapour generated in first effect is entering as a heating media in second effect.

And so on from second to third effect and from third effect to condenser and the whole assembly is connected to the vacuum pump. So, this is the schematic so let us start deriving the governing equation associated to triple effect evaporator. So, first of all we will focus on effect 1. Now, if you remember the 35th lecture of this course there we have derived the governing equation based on material and energy balance for single effect.

So, in the same line we will derive the governing equation for triple effect evaporator also. So, let us focus on effect 1. First of all, we will make the enthalpy balance and this is basically the enthalpy balance of all streams and if you see the first effect as far as streams are concerned we have total five stream F V 0, V 1 and L 1 and along with this we have this condensate also which is again with the flow V 0.

So, while making the balance we can consider enthalpy of feed that is F into hF + Q 1, Q 1 is basically the heat associated with this stream minus V 1. Vapour is generated which is having enthalpy h 1. So, usually we represent enthalpy of vapour by capital H and enthalpy of liquid by small h and that is the usual nomenclature. So, further we have minus L 1 which is containing h 1 amount of heat.

So, in this case you see I am not considering this condensate and that will be clear in next equation when we will elaborate it further. So, I am having F hF + V 0 lambda 0 because here I am considering the latent heat only and after supplying latent heat this condensate exits. So, if I consider this condensate I should also consider enthalpy of vapour with this V 0. So, you see V 0 when I am considering it is basically H 0 – small h 0.

So, that will be nothing, but V 0 lambda 0. So this we have already considered over here. So, finally we have V 1 as F – L 1 and here if you see we have shown this L 0 that should be capital F please make a correction over here. So, F – L 1 should be V 1 and further I am having L 1 as it is H 1 as it is. Further, if I need to rearrange this equation we are considering this capital H as lambda 1 + small h 1 because that is the enthalpy of vapour.

So, considering this as well as this equation we can rearrange and found that F into hF – h 1. So that h 1 will come from here when it will be associated with F + V 0 lambda 0 and then we can have F – L 1 into lambda 1. So in this way I can obtain the enthalpy balance in first effect and further I can obtain the rate equation and what is rate equation Q = UA delta T mean.

And in this evaporator mean temperature is basically the heating media temperature minus effects temperature. So, if I focus on first effect temperature difference should be T 0 – T 1. So, U 1 A T 0 – T 1 should be equal to V 0 lambda 0 because this is the total heat duty of an effect. So, if you see as far as design is concerned what we want to calculate? We need to calculate the area of effect and steam consumption and here we are considering that area of each effect is equal. So, here I am having the governing equation for effect 1.

So, if you focus on these equation we can have this is the final enthalpy balance and this is the rate equation. So, one effect two governing equation. In the similar line, if I ask you to write the equation for second effect how you can write it. You can further write in the same line like L 1 h 1 – h 2. Here instead of V 0, you can write V 1 and that should be equal to F – L 1 and that should be multiplied by lambda 1 when it is entering into the second effect.

And minus we can have L 1 – L 2 lambda 2. In the similar line, I can write this also U 2 A T 1 – T 2 should be equal to V 1 lambda 1 where V 1 is this. So, in this way you can represent each effect with two equation.

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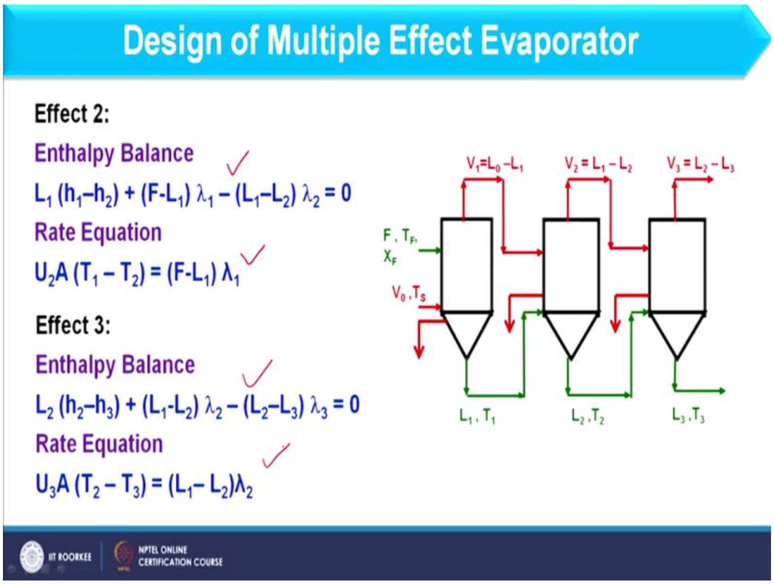

So, here we can have equation for second effect this is basically enthalpy balance of second effect and this is the rate equation. In the similar line, I can find equation for third effect also and we can have enthalpy balance like this and rate equation like this.

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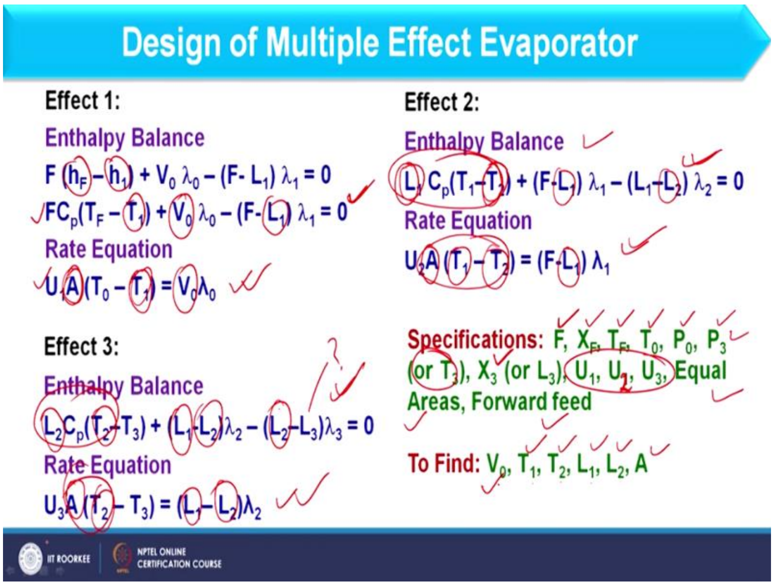

So, if I combinedly see equations of all effect we can observe that each effect is shown with two equation. We have total equation as 1, 2, 3, 4, 5 and 6 and here if you see we have further elaborated hF or h 1 what is the enthalpy of liquid that should be Cp of the liquid into temperature. So, considering that we have elaborated equation that is the enthalpy balance equation of all effects.

Now, if I ask you what are the known parameter over here? So, known parameter we also called that as specified parameter and these parameters are F that is the feed rate XF that is the concentration of the feed, TF temperature of the feed, T 0 P 0 P 3 because last effect pressure or temperature you usually know. So, once I know P 3 I can find out T 3 so T 3 is usually known to me.

And further we have concentration X 3 so X 3 is basically product concentration. So, when you define any evaporator problem you know a priori that the concentration of the feed should be this much when we obtain the product. So, feed should be concentrated from this level to that level. So, you already know the product concentration along with the feed concentration.

Along with this we have U 1, U 2 and U 3 here you should consider U 2. So, all these values are known to me I am considering equal area and forward feed I have considered. So, whatever governing equations we are discussing these equations are specifically for forward feed. If I change the feed sequence these equation will be changed. So, you should understand how to make balance in each effect so that you can make the governing equation depending upon different feed sequences.

So, here we are saying that specified parameters are given and if I ask you that what should be the unknown parameter. If you observe these 6 equations what are the unknown if I focus on this unknown is basically T 1 unknown is V 0, unknown is L 1. In this equation, T 1 and V 0 along with the area. Second effect if I focus on L 1, T 2 L 1 L 2 all lambdas are usually known to us.

And we have area and T 2, T 1 and L 1. So, if we focus on third effect equation we have L 2 unknown T 2 unknown, T 3 is known to me L and L 2. L3 now it is unknown, but you know this while making the component balance this we will see in the solution of these equations and here I am having unknown as area and T 2 and L 1 and L 2. So, if you see these 6 equations of three effects the unknowns are V 0 T 1, T 2, L 1, L 2 and A.

So 1, 2, 3, 4, 5, 6 unknowns are there and how many equations I am having 6 equation. So, 6 equation 6 unknown so unique solution must exist. I understand that you know about this unique solution that is basically we have only one solution and so if you solve this problem how you can solve this because some equation among these are nonlinear in nature. For example, if you focus on this rate equation A is unknown to me and T 1 is unknown to me.

And similarly if I focus on this L 1 is unknown to me T 2 is unknown to me so this will become nonlinear term. In the similar line, this will become non linear term and this term also becomes non linear this term also becomes nonlinear like this. So, if I am having the 6 equation even a single equation is nonlinear in nature you have set of nonlinear equation and you have to solve these equation accordingly. So, to solve these equation we will use a specific method that is Badger McCabe.

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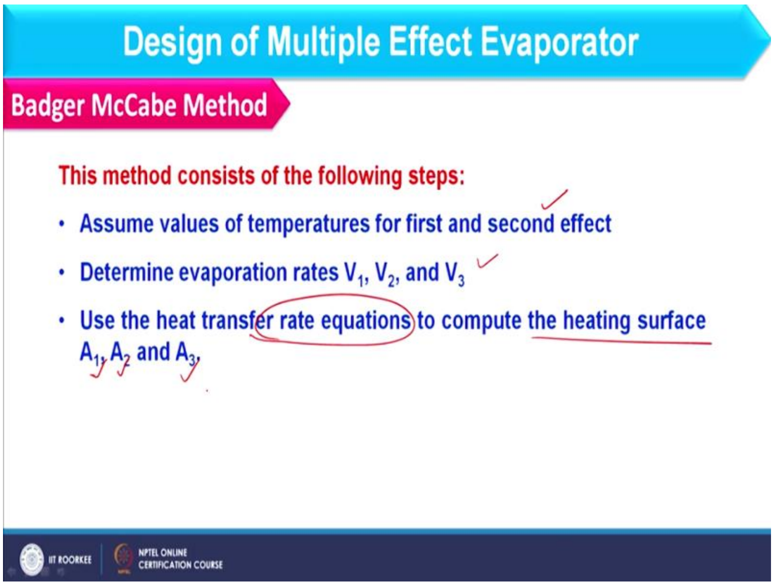

So as far as this method is concerned we should consider some steps and these steps are we have to assume temperature of first and second effect like T 1 and T 2. How we have to assume this that we will discuss. We need to determine V 1, V 2 and V 3. So, instead of that we can say that we need to determine L 1, L 2 and L 3. If I know all these I can automatically calculate V 1, V 2, V 3.

Third step is we have to use the rate equations to find out heat transfer area A 1, A 2 and A 3 and if you remember we have consider heat transfer area equal for all effects, so that should be A. Now if I am observing the variation in area like A 1, A 2, A 3 and these areas are not same we can further redistribute the temperature in such a way so that area should be equal. So this method is basically iterative method. So, let us see all these steps one by one with the help of example so that method is more clear to you.

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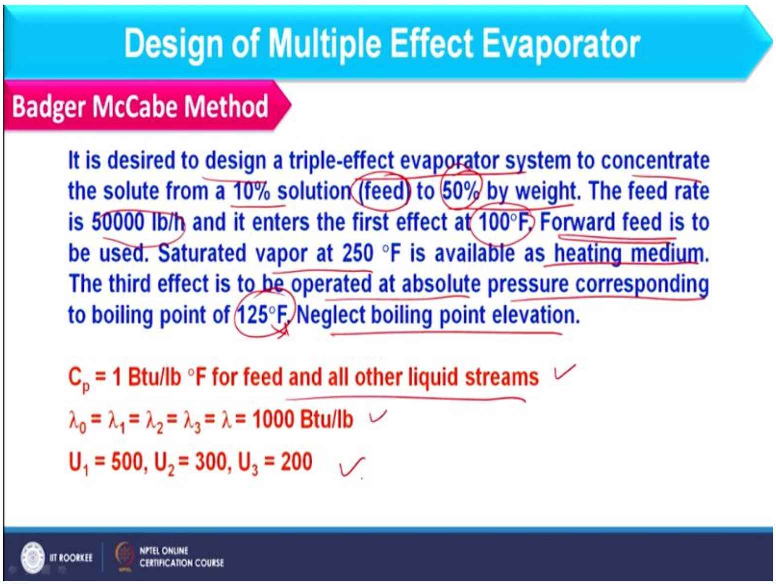

So example is like it is desired to design a triple effect evaporator to concentrate the solute from 10% solution which is the feed to 50% by weight and this is for the product. The feed rate is 50,000 pound per hour and it enters the first effect at 100 degree Fahrenheit. We have to use forward feed and saturated vapour is available at 250 degree Fahrenheit and which is used as a heating media.

Third effect is operated at absolute pressure corresponding to boiling point of 125 degree Fahrenheit and this is corresponding to the vacuum which is generated in third effect and in this problem we have to neglect boiling point elevation. Cp value for simplicity we are considering as 1 Btu for all feed as well as liquid streams. All lambdas are equal and that should be 1,000 Btu per pound.

U 1, U 2, U 3 are known to me as 500, 300 and 200. So, this problem I have taken from (()) (15:56) book and that is also given in Serth book. So, you can follow these books and it is also available in (()) (16:05) book. So, here we are going to solve this problem using Badger McCabe method. Now, the first step is to find out unknown temperature that is T 1 and T 2. Now, if I ask you what is the total driving force available in the system that should be T 0 – T 3.

And the complete driving force in each effect like delta T 1 delta T 2 and delta T 3 will be distribution of this maximum driving force which is T 0 – T 3. So, considering this we have to find out unknown temperature that is T 1 and T 2.

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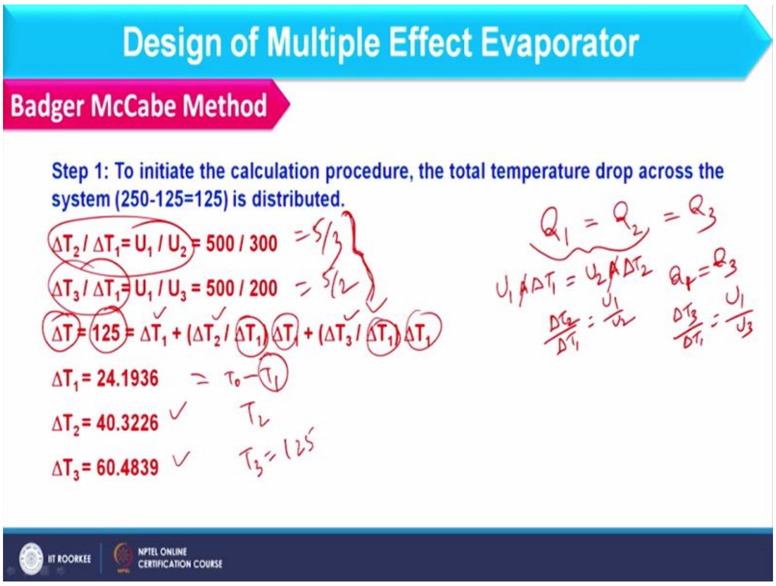

Now to find out unknown temperature we are taking another assumption that equal heat is transferred in each effect. So, if I consider Q 1 heat of first effect that should be equal to Q 2 and that should be equal to Q 3. If I am considering these two and elaborating it what we can observe U 1 A delta T 1 that should be equal to U 2 A delta T 2. So, here we are assuming that each effect area is same.

So this factor will be cancelled out delta T 2 / delta T 1 will be equal to U 1 / U 2 as you can observe here. U 1 and U 2 value I know so that should be 5 / 3. In the similar line, I can consider Q 2 = Q 3 or let us say Q 1 = Q 3 anything I can take. So that should be equal to delta T 3 / delta T 1 should be U 1 / U 3. So, in that way I can obtain delta T 3 / delta T 1 which should be equal to 5 / 2.

As we have already discussed that the maximum driving force available in the system it is distributed in all effects. So, we can say that delta T which is the maximum driving force and that should be equal to T 0 – T 3. It is equal to delta T 1 + delta T 2 + delta T 3 and delta T 1 is basically driving force in first effect and that is T 0 – T 1. In the similar line, I can consider delta T 2 as T 1 – T 2 and delta T 3 as T 2 – T 3.

So, I can write total driving force which is basically 250 – 125 so 125 is available and I am considering delta T 1 + delta T 2 + delta T 3 and divide this by delta T 1 and multiply this by delta T 1 similarly I am considering here. So, considering all these points all these value like delta T 2 / delta T 1 and delta T 3 / delta T 1 are given here. So, we can finally obtain delta T 1 as 24.1936 delta T 2 as 40.3226 and delta T 3 as 60.4839.

And this you know already this is basically T 0 – T 1. So, you can find out T 1 from here and similarly you can find out T 2 and T 3 you can fix at 125. So, in this way we can find the unknown temperature, but that is based on the assumption that equal heat transfer is occurring in each effect. Now second step is to find out L 1, L 2 and L 3. So, first of all we will find out L 3 because in forward sequence final product exits from third effect.

If I consider backward sequence so here I should consider L 1 not L 3. I hope you understand that. Whatever solute is available in feed the complete solute is now available in L 3 assuming that all vapours do not contain any solute.

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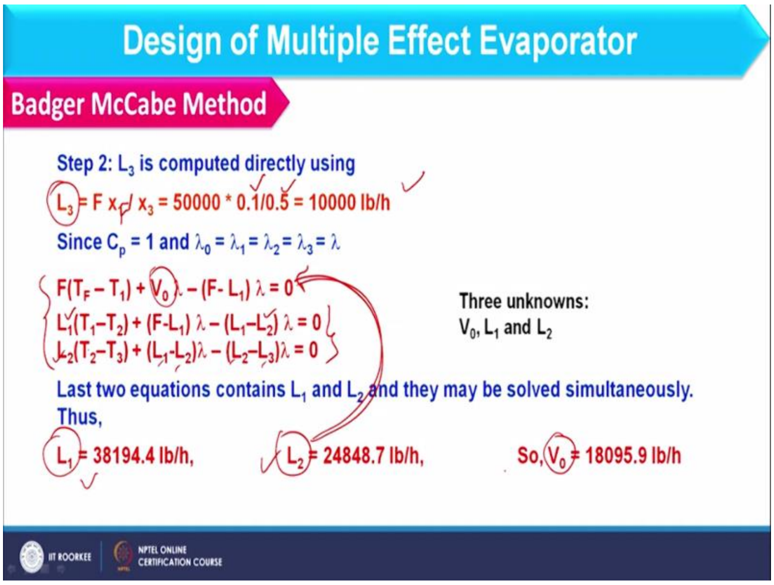

So, here we can make the component balance such as F XF should be equal to L 3 X 3 and feed and product concentration you know already. So you can find out L 3 value as 10,000 pound per hour. Now next you have to compute L 1 and L 2 because if you remember you have 6 parameters in which T 1 and T 2 you have already obtained. Now we have to compute L 1 and L 2.

And for that we should focus on all three enthalpy balance equation or we can say the enthalpy balance equation of all three effects and these equations are like this. Now, if you focus on these two equations what are the unknown over here? We have L 1 T 1, T 2 now I know F I know L 1 is unknown and L 2 is unknown. Similarly, L 2 is unknown T 2 I know T 3 I know L 1, L 2 are unknown L 2 are unknown and L 3 is known to me.

So, if you consider last two equations you can find that the unknowns are only L 1 and L 2 and as we have to two equations and two unknown we can simply solve these equation simultaneously to find out value of L 1 and L 2 and I hope you understand the meaning of solving the equation simultaneously. So, solving these equation we can find L 1 and L 2 like this.

And once I know the value of L 1 and L 2 I can put this values in first effect to find out V 0 so V 0 I can obtain like this. And now next step is to find out heat transfer area because 5 parameters you have already computed. So, to find out heat transfer area we should focus on rate equation.

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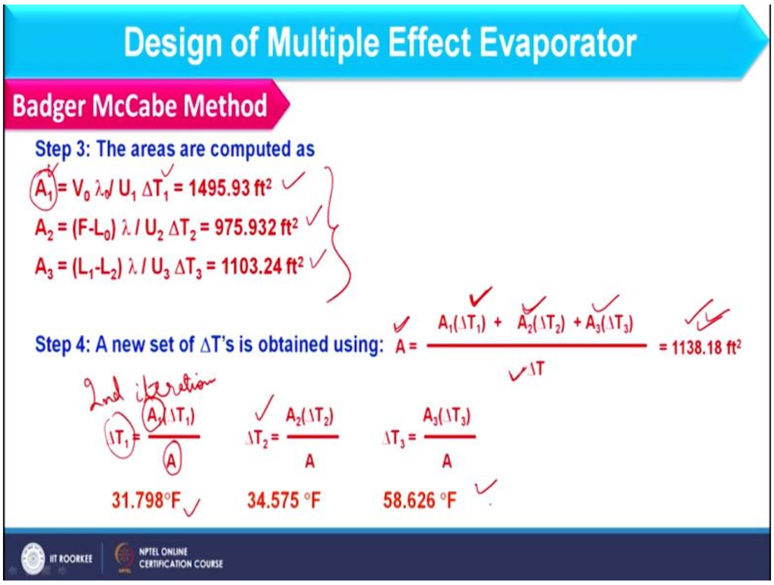

So, let us see the first effect rate equation so that should be equal to U 1 delta T 1 into A because now I am considering different area because area of each effect I have assumed as equal, but now we are considering different areas. So A 1 we can obtain as V 0 lambda 0 divided by U 1 delta T 1 so this value we can obtain like this. Similarly, I can obtain A 2 as well as A 3. So, area you can obtain like this.

So, what is the point to consider over here? Each effect has different area and we already assume that area of each effect is same. So, how I can find the average area of this and we will further redistribute the temperature difference based on the deviation of average area and the individual area. I hope you are getting the procedures because all these values are based on the assumption that equal heat transfer is occurring which is not possible in evaporators.

So, we have to carry out different iterations to reach to the final result and these iteration we will carry out based on different area and equal area which is basically the average area of effect. So, now we can find out the average area of each effect and that area we can weight it based on temperature difference of each effect. So, here I am having A into delta T and this should be equal to A 1 delta T 1 + A 2 delta 2 + A 3 delta T 3.

So, average area you can find as 1,138 and if you observe these area these area differ significantly than this value. So, we have to deviate driving force of each effect like here I am having the second iteration. So, here I am having delta T 1 which is basically the revised value and that should be A 1 delta T 1 / A. How much area we have to obtain and how much we are deviating based on that we will recalculate delta T 1.

So, similarly we can find out delta T 2 and delta T 3 and values of these deltas we can obtain as 31.798 degree Fahrenheit, 34.575 degree Fahrenheit and 58.626 Fahrenheit. So, in this way you can find out the temperature difference and now you can find out T 1 and T 2 value as revised values because you can fix T 0 and T 3 you cannot change these, but T 1 T 2 you can change.

So, for the new values of temperatures you have to find out new values of L 1 and L 2 and so the V 0 and so A 1, A 2, A 3 and again you have to find out the average area. So, this practice should be kept on doing till I will find values of all 6 parameters equal in two consecutive iterations.

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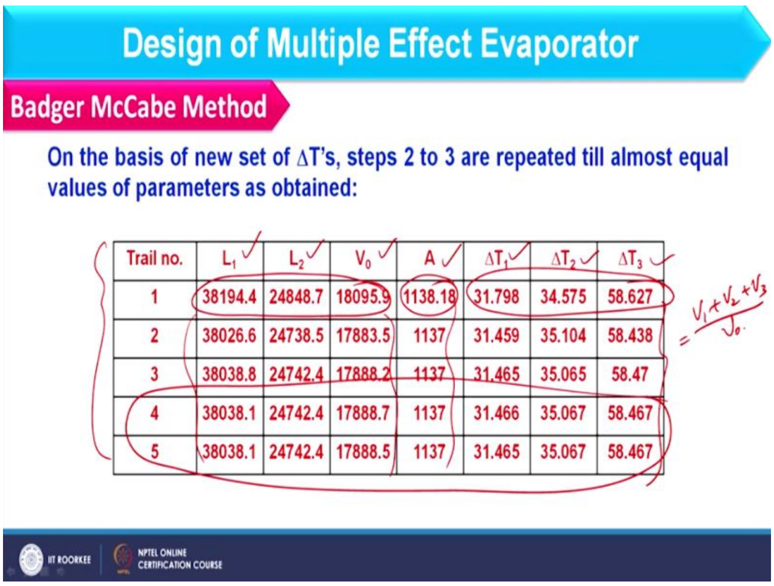

Trail no.	L_1	L_2	V_0	A	ΔT_1	ΔT_2	ΔT_3
1	38194.4	24848.7	18095.9	1138.18	31.798	34.575	58.627
2	38026.6	24738.5	17883.5	1137	31.459	35.104	58.438
3	38038.8	24742.4	17888.2	1137	31.465	35.065	58.47
4	38038.1	24742.4	17888.7	1137	31.466	35.067	58.467
5	38038.1	24742.4	17888.5	1137	31.465	35.067	58.467

And results I have summarized as. If you see here I am having number of trials or the iterations and here I am having L 1 value, L 2 value V 0 A delta T 1, delta T 2 and delta T 3. So, if you see in first iteration I have observed values like this. This is the average area of first iterations and these values we already have seen in first iteration. So, if I change these temperatures the driving force you can further revise like this.

And you can find out other parameters. So, in this way you can stabilize the result where if you observe last two iterations results like this values are equal in two consecutive iterations except value after decimal. So, in this way we can design a multiple effect evaporator. It means you can find out area of evaporator along with the steam consumption. Now once you are having the steam consumption, you can find out steam economy/

And that steam economy should be V 1 + V 2 + V 3 divided by V 0 in this way you can obtain the steam economy because once you know L 1, L 2, L 3 you can compute V 1, V 2 and V 3. So, in this way we can design multiple effect evaporators and here I am stopping this lecture. We will continue design of multiple effect evaporator with another method in next lecture and that is all for now. Thank you.