Process Equipment Design
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Lecture –50
Distillation Column – 3

Hello everyone. This is the 50th lecture of the course Process Equipment Design and in this lecture we are going to discuss the distillation column. So, let us start this lecture. So, as far as this lecture is concerned we are covering the process design over here.

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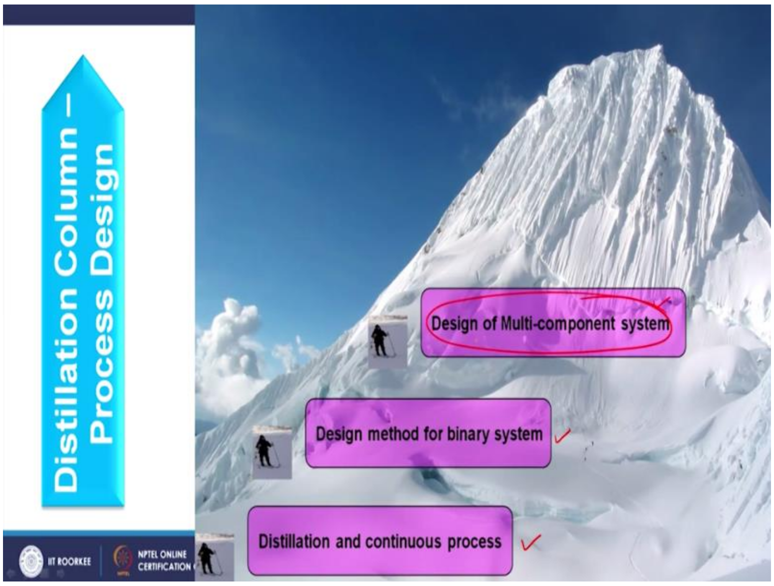

And previously I have covered distillation and continuous process then design of binary system using McCabe Thiele method and then we also have discussed the multi component system. And in this lecture we will further elaborate this topic. So, let us start this lecture.

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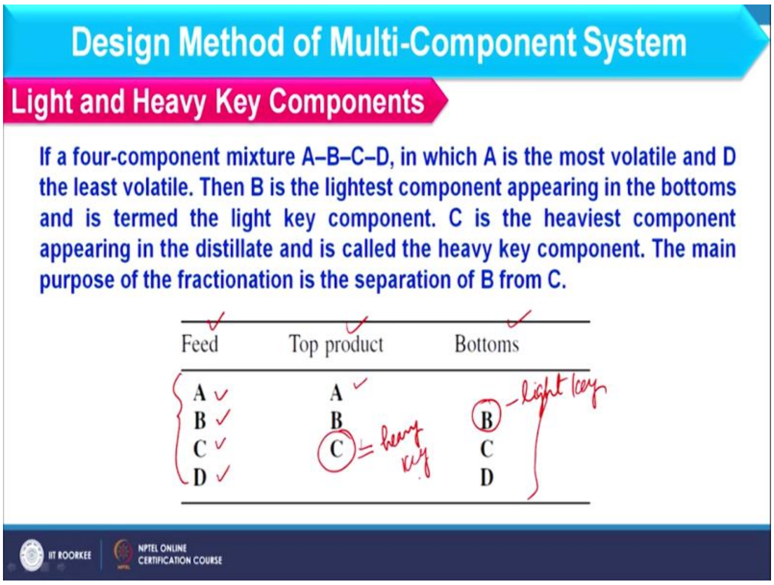

So, here we are going to discuss design of multi component system and before start the design of this we should consider light as well as heavy key component. So, what is basically light key and what is basically heavy key? If we consider the basic definition light key is basically which has more volatility and heavy key which has less volatility. And that is very easy to choose when I am having two component.

One would have larger volatility or higher volatility we consider that as lighter component other one will definitely be a heavier component, but how we have to choose this when I am having multi component system that is important. So, let us say I am having four component A, B, C and D in the feed. And we can arrange these component in the feed top product and bottom product with respect to the volatility.

So, highest component should be placed at top and then we can keep on arranging on component which has lower volatility. So, in this way we can arrange the component with respect to their volatility. So, how I can choose the light key and heavy key. The condition is like lightest component in bottom. Please listen it carefully lightest component in the bottom is represented by light key and heaviest component in the top is represented as heavy key.

So, with this definition if I consider lightest component in bottom and that component is B. So, this is considered as the light key. Similarly, heaviest component in top is the heavy key and which is basically this C component so this we consider as the heavy key. So, in this way we can consider B as the light key and C as the heavy key and we will design the system based on the separation between B and C.

I will not focus on A and B that will be separated along with these components only, but my main focus will be to separate B component from C. So, let us see how we can design the multi component system and for that we have the method like Hengstebeck's Method.

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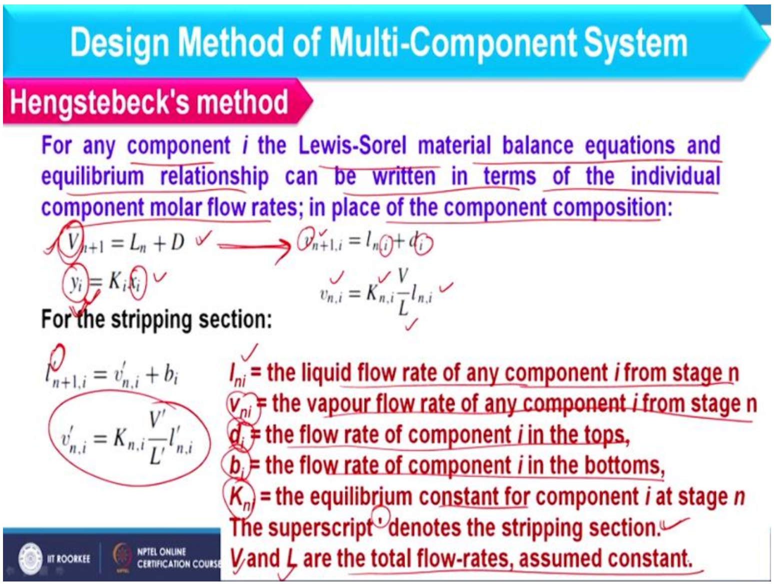

So, according to this method for any component i the Lewis-Sorel material balance equation and equilibrium relationship can be written in terms of individual component molar flow rate in place of component composition. So, what we can consider over here that there are two points. First is we have to consider individual molar flow rate of each component and second is at the place of composition I should consider molar flow rate.

So, let us see the material balance changes with respect to this consideration. So, here I am having the balance at the top and that is basically above feed so V n + 1 should be equal to Ln + D this equation we already have seen previously and equilibrium relation will be y i should be equal to K i into x i. So, K i basically equilibrium constant and when we consider this in Hengstebeck's Method it is represented by small v.

You can see here I am having total V which is here I am having capital V which is nothing, but the total flow rate. So, here for each component we can have small v so small v n + 1 i should be equal to l n i + d i where i is the ith component. So, in the similar line I can write this equilibrium relationship as small v n i divided by capital V. So, it will give the value of this. And that should be equal to K n i and it should be multiplied with l n i divided by L. So, that will be this value.

So, in the similar line we can consider equations in stripping section as l dash n + 1 i and dash you can understand this is basically for stripping section it should be equal to v n i dash + b i and similarly this is the equilibrium relationship. So, here we have different nomenclature which we have used. And these are basically l n i which is the liquid flow rate of any component i from stage n.

V n i vapour flow rate of any component i from stage n and d i is the ith component which is available in the distillate, b i is the ith component available in the bottom product, K n i equilibrium constant of component A and here we can consider prime or dash to denote stripping section that is the known fact. Capital V and capital L are the total flow rate that we consider as constant.

So, in this way we consider Hengstebeck's Method where flow rate of each component is considered. Now, why it is considered so? When we consider Hengstebeck's Method it basically counts the fact and that fact is basically when I am having heavy key as well as light key. So, obviously I will have some non key component also. Like light non key and heavy known keys.

So, this method considers that flow rates of non key components are constant and that we consider as the limiting flow rates. So, if I consider the constant flow rate of non key component I already know the total flow rate like Capital V and capital L I already know. So, if I deduct the non key component flow rates from the total what I will get? I will get the flow rate of key components only.

So, in that case what basically we are considering? We are considering that the multi component system is now transpose to binary system where I have only two component the light component and heavy key component. So, that is the basic fact about the Hengstebeck's Method that it considers or it transposes multi component system into binary system. And then we consider that as pseudo binary system.

So, now I am having binary system only so we can solve the same problem considering McCabe Thiele method. So, Hengstebeck's Method is basically pseudo binary system based method.

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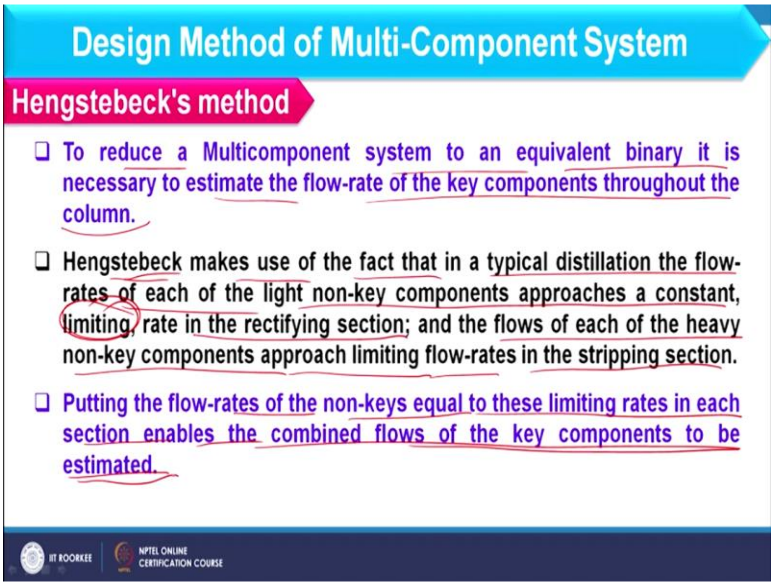

So, let us see how we can proceed further with this method. So, to reduce the multi component to the equivalent binary it is necessary to estimate the flow rate of key components throughout the column. And to do that Hengstebeck's make use of the fact that in a typical distillation the flow rate of each light non key component approaches a constant which we consider as limiting flow rate and that we consider as the limiting flow rate in rectifying section.

In the similar line; flows of each heavy non key component approach limiting flow rates in stripping section. So, this is the fact that we have already discuss that it considered the flow rate of non key component as constant which we also consider as limiting flow rates. And further putting the flow rates of non key is equal to these limiting rates in each section enables the combined flow rate of key components to be estimated.

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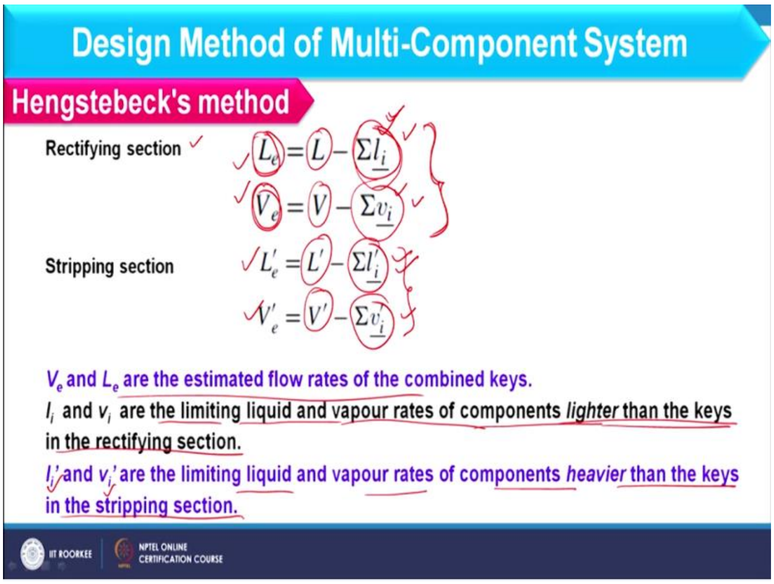

So, let us see how to do that? Here, I am having the rectifying section and here we have the equation. So, L e and V e are basically the flow rate of key components. And here we have summation l i and summation v i these are basically the limiting flow rates of non key component. And if I deduct these from the total flow rate I can find out the flow rate of key component.

And this we are considering in rectifying section only and therefore l i and v i are basically considered for non light key component. And similarly here I am having summation li dash and summation v i dash. These will be for the components which are non heavy key and these are the limiting flow rates. These we deduct from the total flow rate to find the flow rates of key components.

So, as far as that L e V e L e dash V e dash is concerned these are the flow rates of combined keys as it is shown over here. So, l i and v i are basically the limiting liquid and vapour rates of the component lighter than the keys in the rectifying section. And similarly l i dash and v i dash are limiting liquid and vapour rates of components heavier than the keys in stripping section.

So, in this way we can represent the complete multi component problem into binary system and now we can see how to find out limiting flow rates of non key components.

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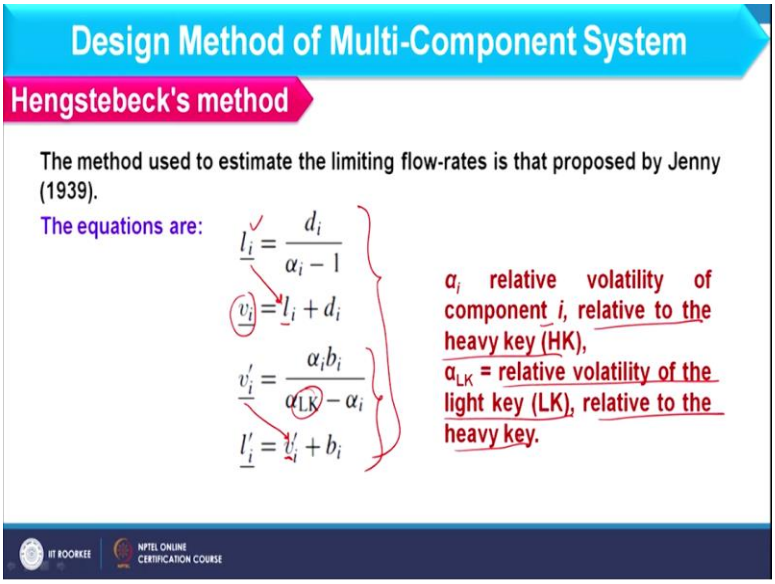

So, to do that we have these equations where l i underscore is equal to d i / alpha i – 1 and v i underscore is basically l i underscore over here and that should be added to d i. So, this will be used over here. Similarly, for stripping section we can consider this and this should be used over here, so it is basically v i dash underscore. So, this correction you can consider and we can have alpha i which is the relative volatility of component i relative to the heavy key.

And alpha LK is basically relative volatility of light key relative to the heavy key. So, when we consider multi component system relative volatility we can always obtain based on heavy key.

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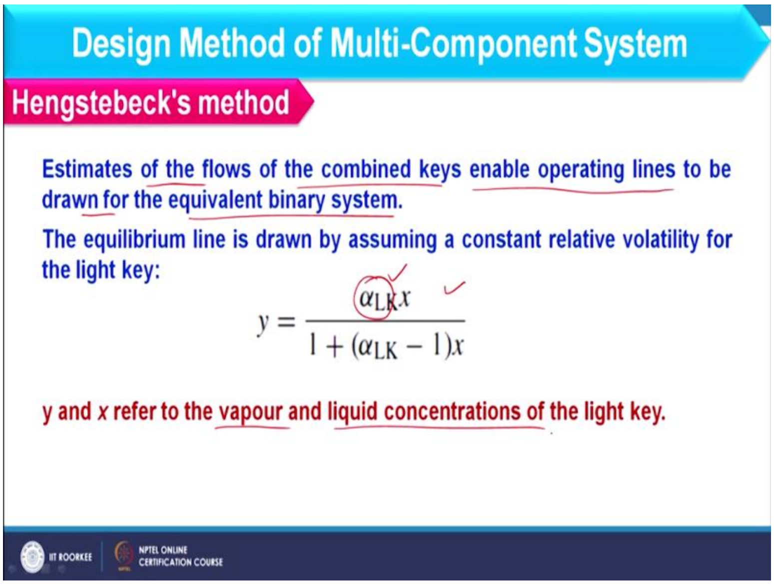

And now we will consider the Hengstebeck's Method as it estimates the flows of combined key which enable the operating lines to be drawn for equivalent binary system. So, for equilibrium line we can find out the relation as y = alpha LKx divided by 1 + alpha LK – 1 into x. So, this we have already discussed this is basically the relative volatility of light key with respect to heavy key

And y and x refer to the vapour and liquid concentration in light key. So, now once the problem is transpose into binary system we can consider McCabe Thiele method to find out number of trays for such system so that is basically the Hengstebeck's Method. Now, we will illustrate this method with the help of some examples.

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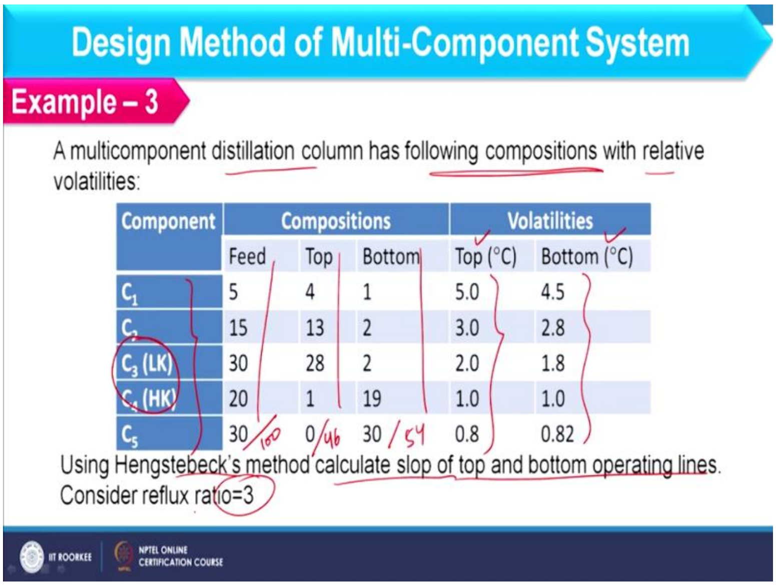

So, let us say we have example 3. In this example multi component distillation has following compositions with relative volatility. So, you see here I am having the component like C 1, C 2 to C 5 and we can already have the light key as well as heavy key and the compositions of feed top and bottom are given to us. So, if you consider this feed total is basically 100 and here at the top it is 46 and at the bottom it is 54.

And as far as volatilities are concerned at top temperature and bottom temperature of distillation column these are the volatilities. So, what we have to do? We have to use Hengstebeck's Method to calculate slope of top and bottom operating line where reflux ratio is considered as 3. So, in this way we need to find out the top and bottom operating line slopes. So, let us start this using Hengstebeck's Method.

So, as far as that Hengstebeck's Method is concerned first of all we need to find out the average volatility.

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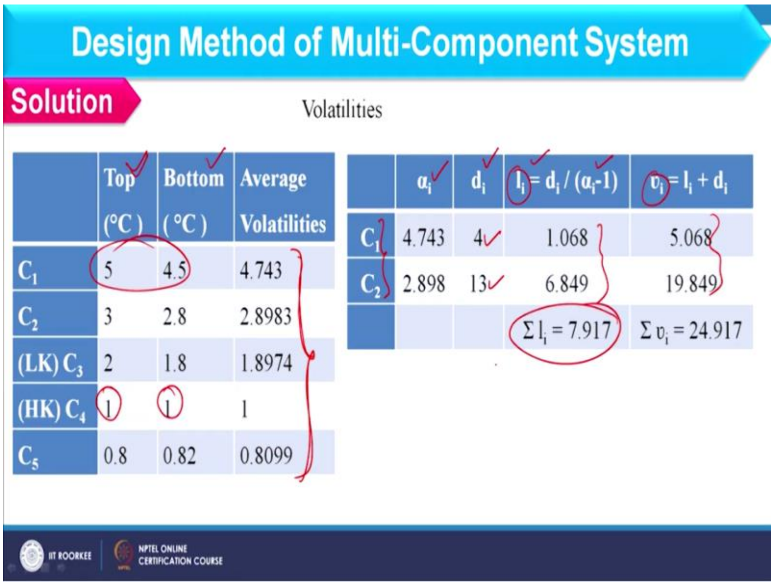

So, as far as average volatilities are concerned these are basically relative volatilities because if you see corresponding to heavy key we have value 1. So, all these volatilities at top and bottom temperature are relative volatility. So, we can simply make the geometric mean of that to find out average relative volatilities of different components so that you can do it is not difficult.

And now we have to find out limiting flow rates of non key. Now, if you consider C 3 as a light key. So, C 1 and C 2 are non light keys and if C 4 is the heavy key C 5 will be non heavy key. So, accordingly you can choose the limiting flow rates of non key components. So, here if I am having C 1 and C 2 we can find out relative volatilities which are already available and here we have the flow rate in distillate corresponding to C 1 and C 2.

So, you can see here I am having 4 and 13 so these values are given over here and then we can have limiting flow rates of l i as well as v i so that is so that is basically the l i underscore and v i underscore in usual expressions which we have discussed previously. So, simple calculation is there you can find these values and addition of this will give the summation li and summation vi.

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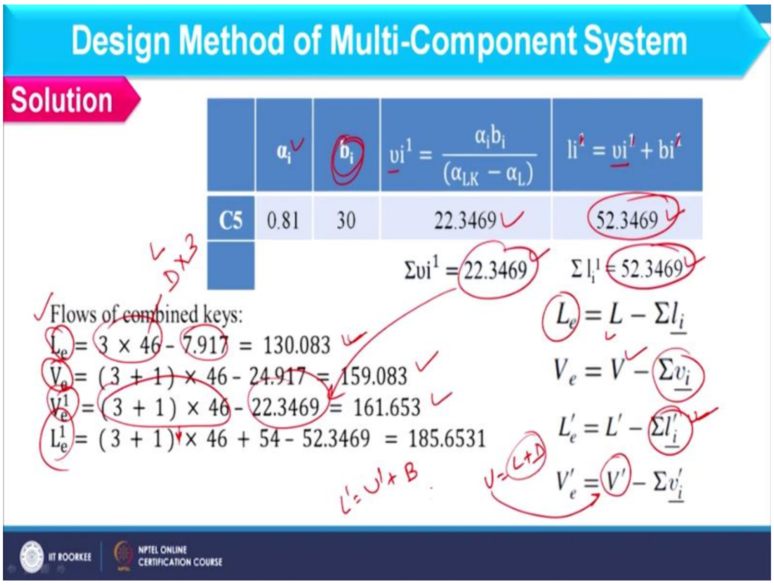

And in the similar line we can find out the limiting rates of non heavy key as C 5 is the only component available in that category. So, we can find out alpha i for that and bi which is given as 30 in the table and here we have v i dash this is not 1 so you consider all these as prime or dash and here you can find out vi prime underscore as this and then we can simply add 30 to this to find out this value. So, summation you can find like this.

And now we have to find out flow rates of top operating line and bottom operating line and that flow rate is L / V at top and L dash / V dash at the bottom. So, in that case we first consider the flow rate of key components and how we do this? We know total flow rate and from that we will deduct limiting flow rate of non keys. So, here we have the flow of combined keys.

So, L e is basically the combined key flow rate in liquid phase so that should be 3 into 46, 46 is the total distillate and 3 is the reflux ratio so that is nothing, but the L. So, you can see L e is basically L – summation l i. So, that we can consider over here this value we have already calculated. So, this is the value of L e. Similarly, for V e how we can consider for that I need to V and that V should be equal to L + D.

So, we can consider 4 into D and minus this factor so 159.083 we can obtain V e dash we can obtain as V prime minus this factor. So, this will be nothing, but equal to this only. So, that we can consider and deduct this value and so we can find V e prime as 161.653 and L e prime we can obtain considering this equation where L dash is basically V dash + B. So, that B is

54 and V dash we already have computed over here so that we can consider here as well. And from this we will deduct this value and we can find the L e dash as 185.65.

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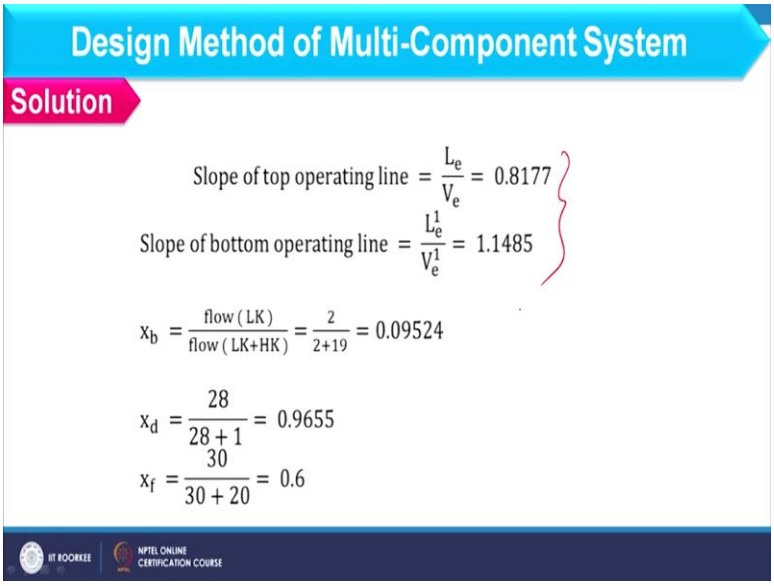

And similarly we can simply calculate the slope of operating line like this.

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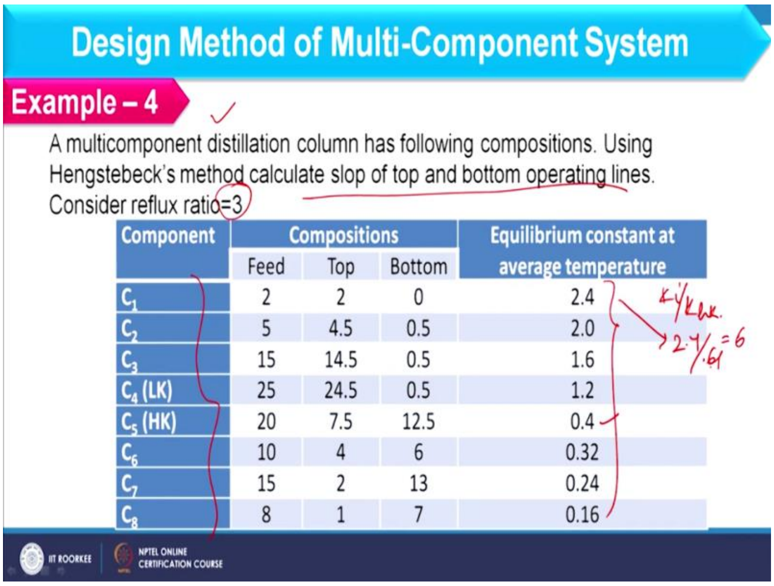

So, here I am considering another example where Hengstebeck's Method is used to again calculate the top and bottom operating line reflux ratio is 3, but here we have more number of components and in this case I am giving equilibrium constant at average temperature. So, how I can find the relative volatility that should be ki / k heavy key. So, considering this we can simply find for this 2 / 4 divided by this that is 0.4 and that should be equal to 6.

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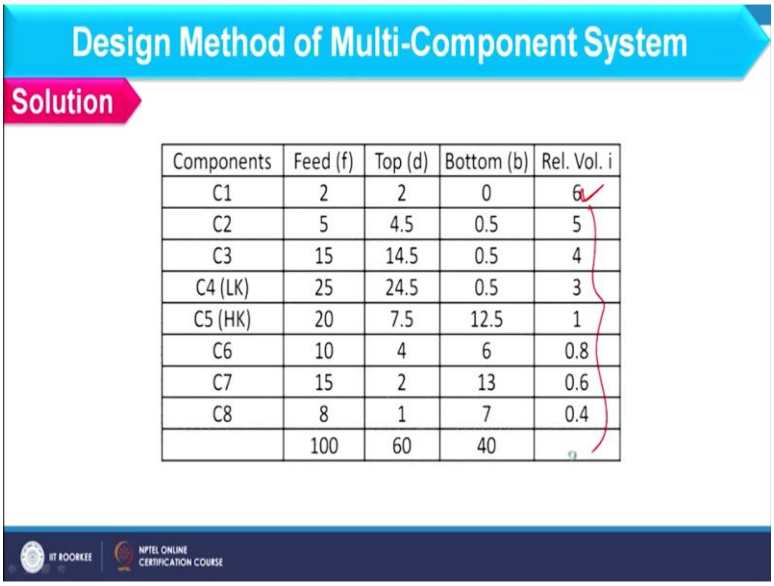

So, in this way you can find out relative volatility and accordingly we can calculate relative volatility of other component.

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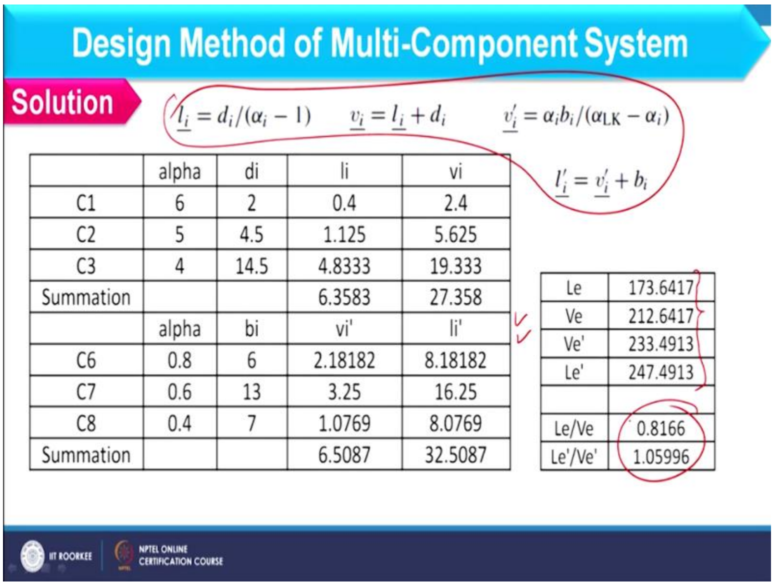

And we can simply find out all these values which are shown in these tables and L e, V e, V e dash L e dash we can find as we have discussed in previous example and these are basically the slopes of operating lines at top and bottom. So, in this way we consider the Hengstebeck's Method. Now we can have another method to calculate number of trays in multi component system and that is Erbar-Maddox method.

You can ask that in Hengstebeck's Method we have not calculated number of trays. So, that you can obtain by considering McCabe Thiele method once you have transpose the problem from multi component to binary component. So, that is basically the repeated exercise so I have not considered that.

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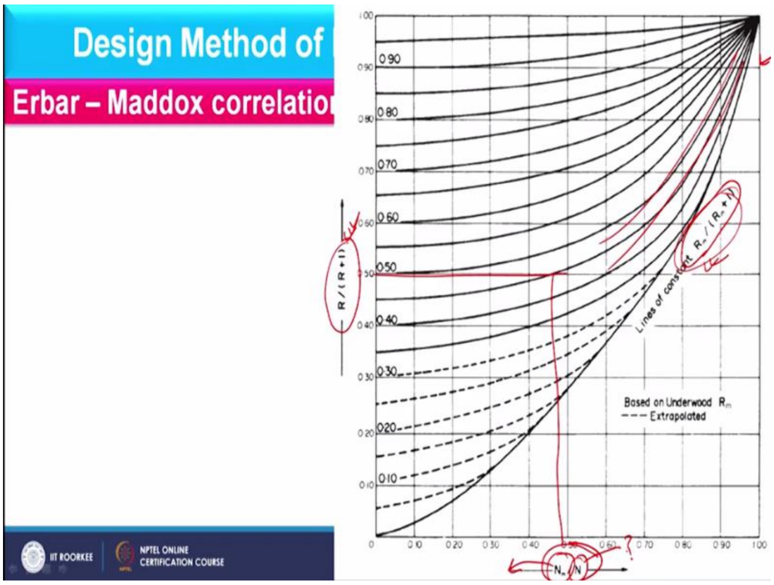

So, let us discuss Erbar-Maddox method now and that is the empirical correlation based. And here we have this graph which is all about this method. If you consider x axis of this that is N m / N N m is basically minimum number of trays and N is the actual number of trays which you have to find. If you see here I am having different lines and these lines correspond to R m / R m + 1 and that R m is basically minimum reflux ratio.

So, that we can consider in these lines and on y axis we have R / R + 1 so that is the actual reflux ratio given in the problem. So, you basically know this and you can also calculate this so depending upon all these value you can find the N m / N. N m number of trays you can also calculate and so you can find out N number of trays that is the actual number of trays for the given separation. I hope method is clear.

Now, we will see the value of different terms. First of all we will find the value of Nm that is the minimum number of trays and that we can obtain at total reflux condition.

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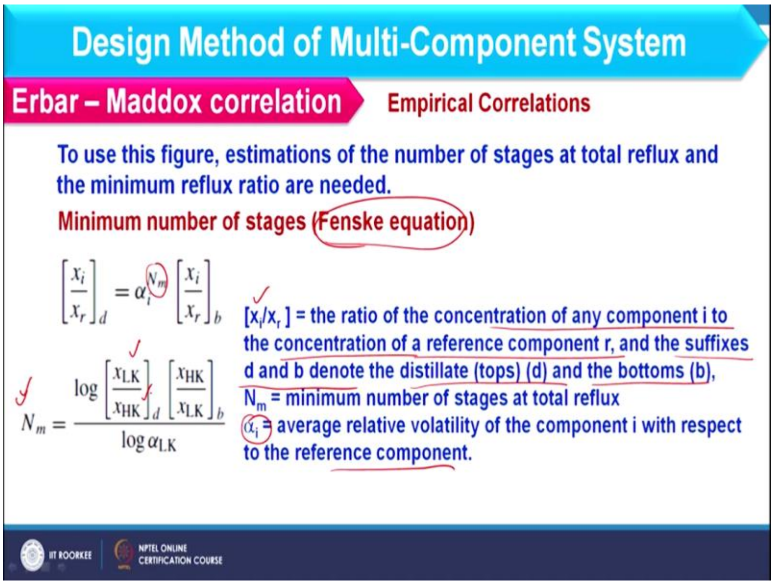

So, for minimum number of stages calculation we can consider Fenske's equation as you can see over here. So, this is the Fenske's equation where xi / xr is the ratio of concentration of any component i to the concentration of a reference component r and the suffix d and b denotes distillate as well as bottom. So, here I am having Nm as minimum number of stages, alpha i is the average relative volatility of the component i with respect to reference component.

And reference component is usually the heavy component. So, when we resolve this we can find this expression to find out minimum number of trays based on light key as well as heavy key. So, here also we should consider selection of key component first and based on that we can use this equation.

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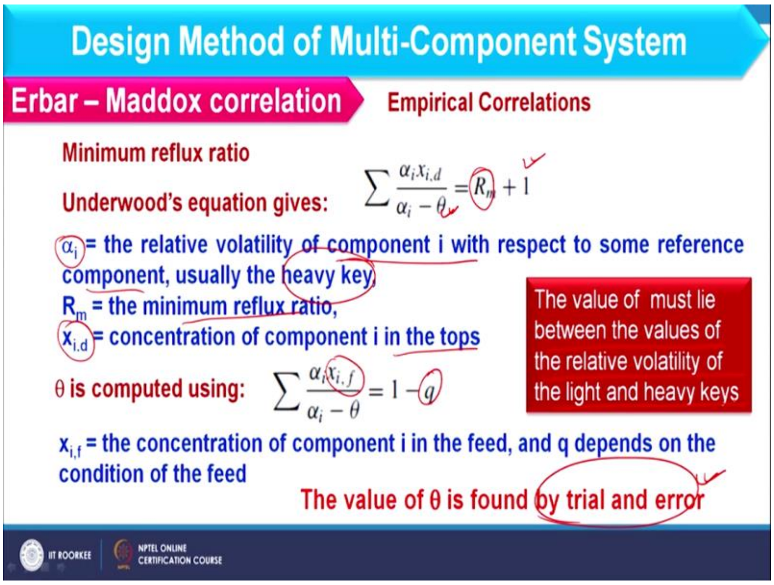

So, once I am having Nm value we can find minimum reflux ratio value and that we can obtain through Underwood's equation. And Underwood's equation is given as where summation alpha i x i d / alpha i – theta should be equal to R m + 1. So, this R m is basically minimum reflux ratio alpha i is the relative volatility of component i with respect to reference component and that is usually the heavy key.

R m minimum reflux ratio that we have already discussed X i d is the ith component in distillate. And how we can compute theta so for this we can have another equation which depends on the feed composition of ith component and we can also consider q line over here. So, based on that we can find the; theta value which can be obtained by trial and error method. So, how I can use the correct value of theta?

The correct value of theta must lie between the values of relative volatilities of light and heavy key. So, in this case you may have number of values of theta so wherever the value will lie between relative volatility of light key and heavy key that value you can consider for theta. So, this is basically Erbar-Maddox method and quickly we will cover the example related to that.

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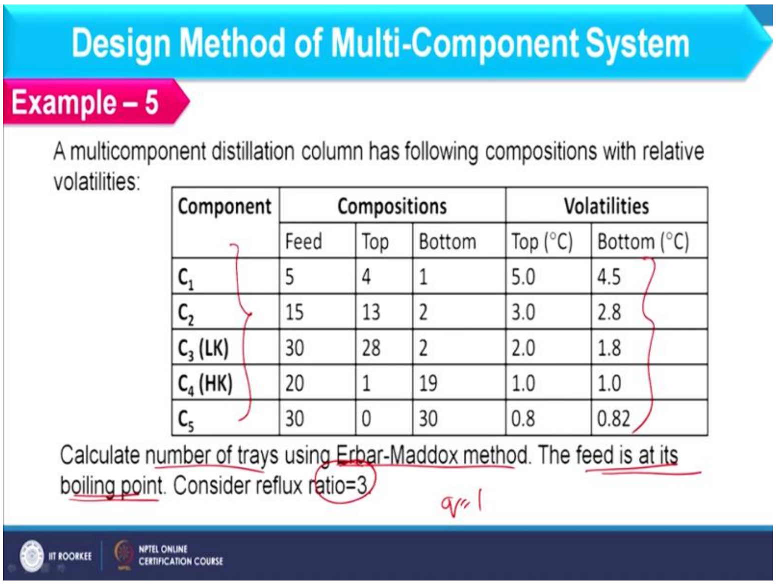

Component	Compositions			Volatilities	
	Feed	Top	Bottom	Top (°C)	Bottom (°C)
C_1	5	4	1	5.0	4.5
C_2	15	13	2	3.0	2.8
C_3 (LK)	30	28	2	2.0	1.8
C_4 (HK)	20	1	19	1.0	1.0
C_5	30	0	30	0.8	0.82

So, in this case we can have the same example which we have discussed as example 3 for Hengstebeck's Method. So, all these points you know already and here we have to compute number of trays using Erbar-Maddox method. So, feed is at boiling point where q should be 1. We have to consider reflux ratio as 3. So, let us start that.

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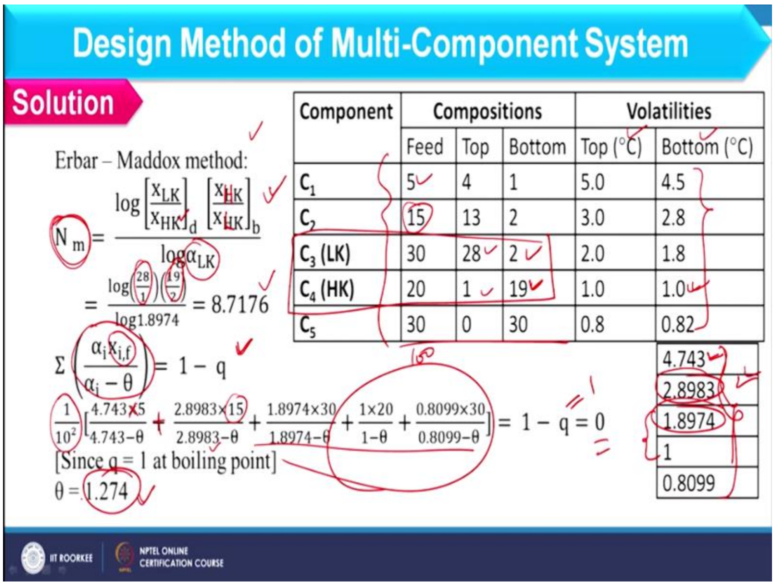

So, here we have relative volatility with respect to heavy key at top as well as bottom and average of that we have already calculated in previous examples that you can refer. So, these values are already available to you and now we consider Erbar-Maddox method and first of all we will find minimum number of trays that is Nm and that is the expression. So, you can see we have to focus on this condition so x LK in distillate.

So, this is basically 28 and that is heavy key in distillate so that should be 1. So, that you can consider over here LK at bottom that is basically 2 divided by 19. So, here you can consider this is basically H and this is L. So, this correction you should consider and here if you consider heavy key is bottom so that should be 19 and light key in bottom as 2 so that you can consider as 19 / 2 and that should be divisible alpha LK.

So, that is nothing, but this value. So, you can find N m as 8.7176 and this equation we can use to find out theta value. And in this equation this X i f is basically the fraction of component i in feed. So, if you see the total feed is basically 100 so that we can consider 1 / 100 over here and then we keep on expanding this expression. So, that should be alpha i. So, for first component 4.743 into 5 that is given over here divided by this alpha i – theta + second component this is alpha i and this is the xi and again alpha i we can consider.

And so we keep on adding this for 5 different components and that will be equal to 1 – q where q will be equal to 1. So, that we can consider as 0. So, when we solve this we can find theta value as 1.274. We can obtain more values also, but we should choose the value which will fall between relative volatility of light key as well as heavy key as you can consider this value.

So, in this way we can find out theta value and further we have to find out minimum reflux ratio using Underwood's equation.

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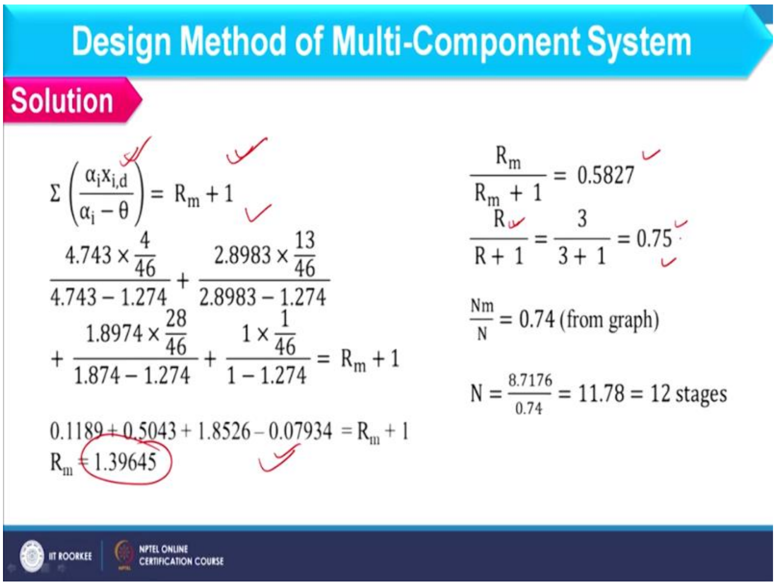

So, this is the Underwood's equation. Solving this equation because all components you know here we can have R m value as 1.39645 I think you can solve this very easily. There is no problem. So, once I am having R m value we can find out R m / R m + 1 and reflux ratio in the problem is given as 3 so we can find R / R + 1 and now we can use the graph. You can see Rm / Rm + 1 is 0.58 and this is 0.75.

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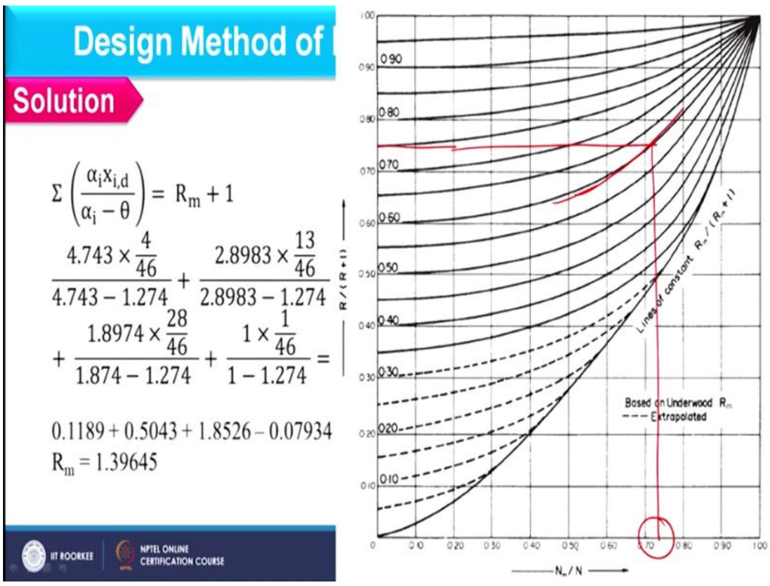

So, this is the graph where R m / R m + 1 is 0.58 so that should be almost 0.6. So, this is the curve and 0.75 is R / R + 1 so that you can consider this line. So, wherever it will cut this line we can find N m / N using this point.

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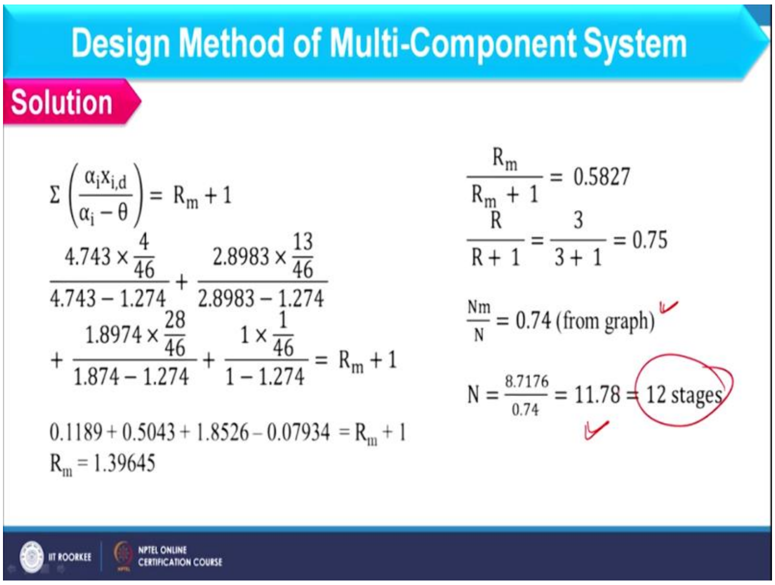

So, accordingly N m / N you can find as 0.74 and so the number of stages N you can find as 11.78 so that should be equal to 12 stages. So, in this way Erbar-Maddox method works.

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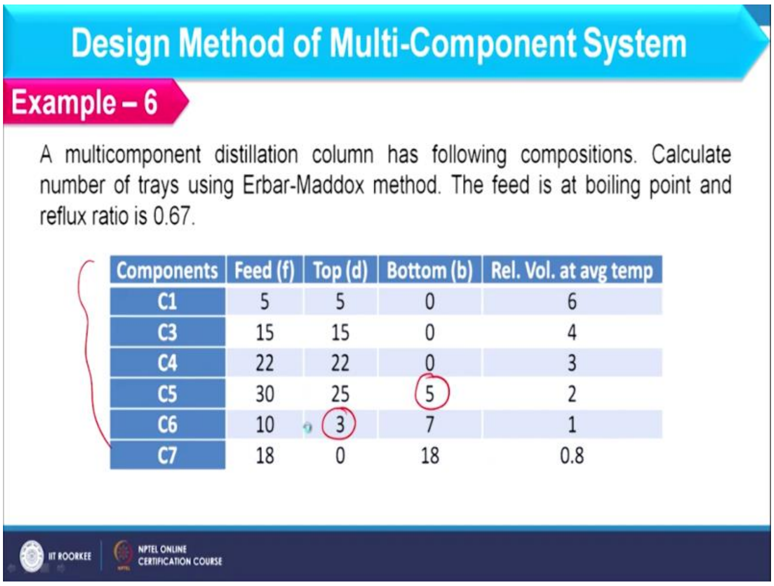

And so we will cover the second example of Erbar-Maddox method quickly and that is this example where this is basically the light key and this is the heavy key based on the simple definition of it.

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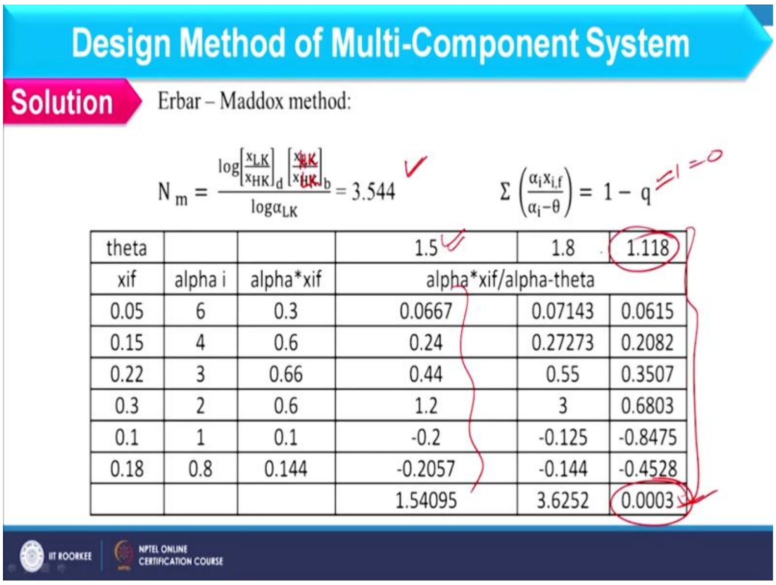

And we can find minimum number of trays using Fenske's equation. So, this you please change to this and the N m we can find as 3.54, q value should be 1. So, we can find the theta value also. So, this is another method to find out theta value either you can simply calculate that from the calculator by putting the whole equation or you can simply keep on assuming the theta value and keep on calculating this till you will find the value should be equal to this and that should be 0. So, this is almost 0 so we can choose theta value as 1.118.

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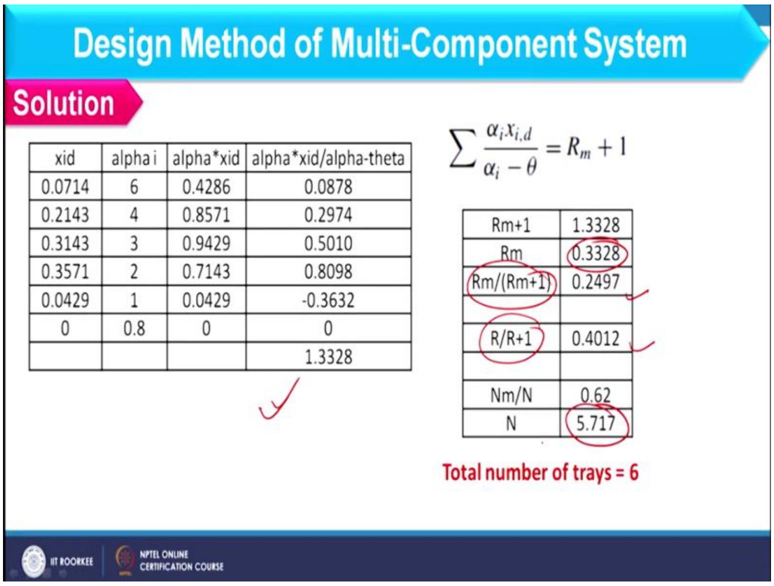

And after that we can find out Rm by this calculation so that Rm is 0.3328 then Rm / Rm + 1 we can find R / R + 1 we can find and so the number of trays we can find using the graph which we have discussed in previous example. So, total number of trays we can find as 6.

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And here I am having some of the references about this and this is the summary of the video and this is the summary of last three lectures of distillation column.

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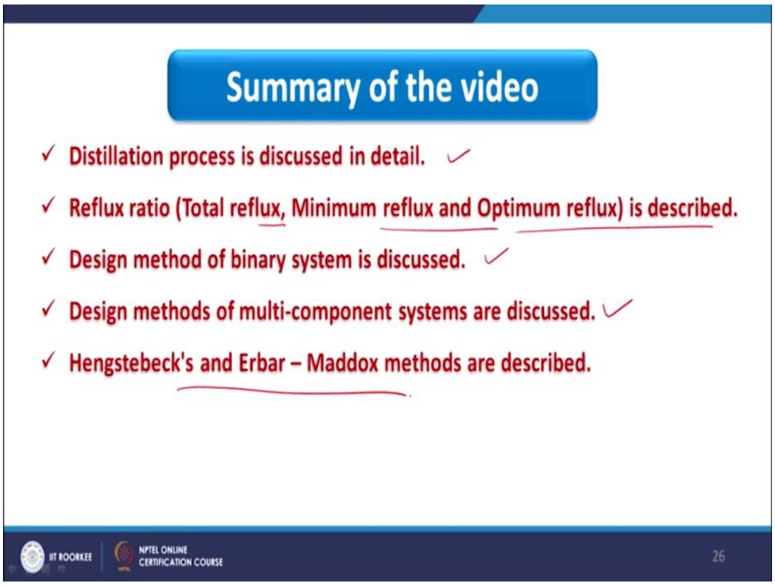

And summary goes as distillation process is discussed in detail. Reflux ratio that is total reflux, minimum reflux and optimum reflux is described. Designed method for binary system is discussed, design method of multi component system is discussed and we also have discussed Hengstebeck's as well as Erbar-Maddox method and that is all for now. Thank you.