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

**Lecture –49**
**Distillation Column – 2**

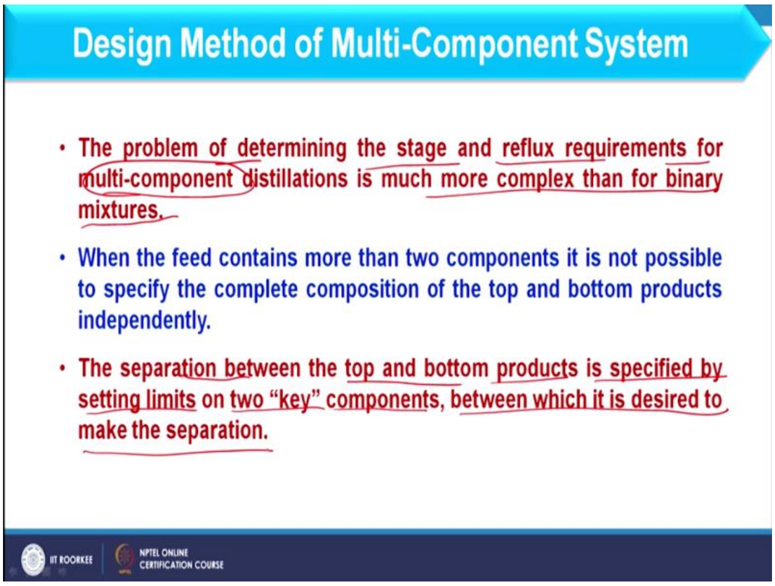
Hello everyone. I welcome you all in this lecture which is 49th lecture of the course Process Equipment Design and here we are going to discuss the distillation column and for that we are considering the process design. Now, as far as this lecture is concerned here we will address one milestone, but before that let us focus on the complete milestone which we are going to cover in this topic that is distillation column process design.

**(Refer Slide Time: 00:57)**


So, we have some milestones like first we have discussed the distillation and the continuous process and we already have covered the design method for binary system and here we have focused on McCabe Thiele method and after that we will consider design of multi component system. And then plate efficiency and finally we will focus on plate hydraulic design. So, in this particular lecture we will consider this topic that is design of multi component system.

Now as far as this multi component system is concerned obviously that you understand that in this case we have more than two components which are available in the feed which we have to separate using distillation process.

**(Refer Slide Time: 02:01)**




So, let us discuss some facts about that. So, when we focus on multi component system the problem of determining the number of stages and the reflux requirement for such system it is much more complicated or complex in comparison to when we consider or calculate these in binary system and that you understand because handling multi component system is complex in comparison to binary system.

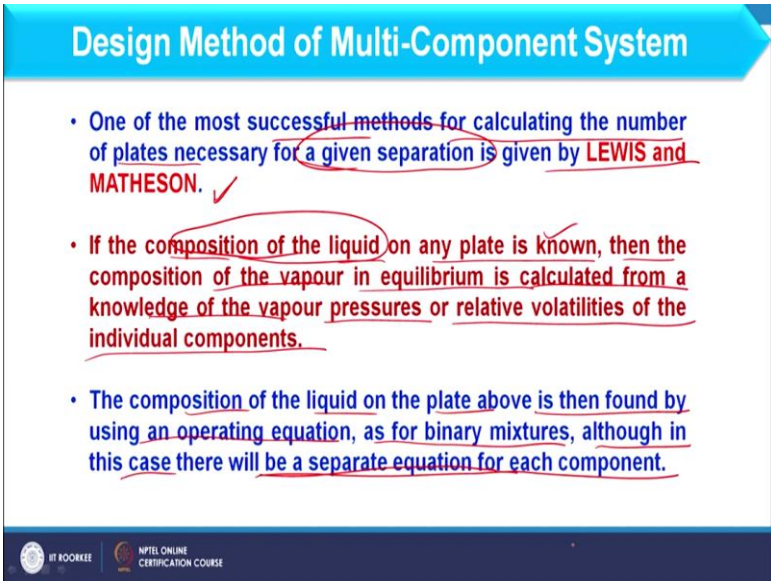
So, as far as this multi component system is concerned if I am having more than two component we call that as multi component system. So, in this case we cannot get the complete composition of top and bottom product independently. Some of the product will be available in top and some of the product will be available in bottom. However, in the case of binary system we may get the clear composition at top as well as bottom.

So, how we have to handle this problem? The separation between top and bottom products is specified by setting limits on two key components between which it is desired to make the separation. So, when we deal with the multi component system among these components we choose any two components between which we desire to have complete separation or the separation.

If it is not complete at least significant separation should occur between these components. So, when we select such component we consider these components as the key components and separation we consider between these components only. However, we have some methods also in which without selecting these key component we can calculate the number of stages and the reflux requirement depending upon the multi component system.

So, in this lecture we will discuss one of such method and that method is given by Lewis and Matheson.

**(Refer Slide Time: 04:27)**

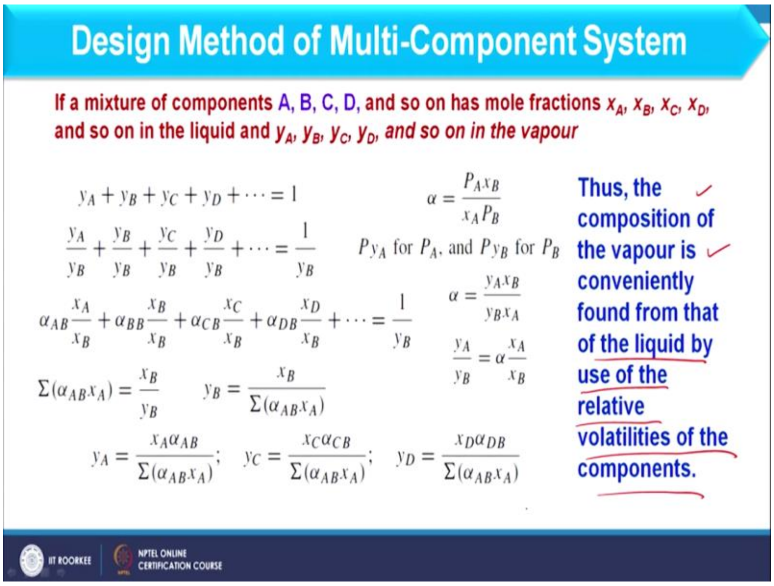



So, one of the successful method for calculating number of trays or number of plate for a given separation is proposed by Lewis and Matheson. Now, as far as this method is concerned what it considers if the composition of the liquid on any plate is known, the composition of liquid when it is known on any plate then the composition of vapour in equilibrium with that liquid is calculated from the knowledge of vapour pressures or relative volatilities of individual component.

So, we can use the relative volatility as well as the pressure drop data to find out the unknown composition of the vapour which is in equilibrium with the liquid. So, that fact is considered by Lewis and Matheson method and further the composition of liquid on the plate above is then found by using an operating equation as for binary mixture. Although, in this case there will be a separate equation for each component.

So, in this way we define the operating condition with respect to each component and then we can calculate the liquid composition on the plate which is above then on which we have calculated the vapour composition which is in equilibrium with the liquid as we have discussed in second point in the slide. So, now we will demonstrate this method and then we will illustrate the calculation using this method with the help of example. So, let us see how this method works.

**(Refer Slide Time: 06:31)**




If I consider the mixture which is having four component let us say A, B, C and D and we can consider much more component than that. So, the component A, B, C and D and so on it means other components are also available in the mixture the composition of these components are let us say X A, X B, X C and X D and so on. And obviously when I am considering X A it means this is basically corresponding to the liquid streams.

So, if these mole fractions are available corresponding to these component we can consider further that y A, y B, y C, y D and so on in vapour streams. So, this is basically the normal nomenclature that X we denote for liquid stream and Y we consider for vapour stream. So, if I am having such components then y A + y B + y C + y D and so on should be equal to 1 accordingly we can consider the vapour composition.

And the complete composition should be equal to 1 that is basically the normal condition we consider for composition. Now, further if I divide the whole equation by y B you can consider any other component also. So, here I am having y A / y B + y B / y B then + y C / y B and then y D / y B and that should be 1 / y B. In this way we can represent the equation and when I divide all compositions by the same amount from left hand side as well as right hand side it is not making any difference.

So, if I am having this type of representation I can represent the equation or I can represent the terms in this way where alpha AB is the relative volatility and that I can relate with the composition in liquid phase of the same component as we can see in this equation. Now the point is how we can obtain each term of that we can understand through this equation where alpha is related to partial pressure as well as the composition in liquid phase.

And that alpha is nothing, but the relative volatility as we have discussed in the previous slide. Now, if this is the equation what we can consider further? We can replace P A with P y A that is the partial pressure of component A should be equal to total pressure into the composition in vapour phase that is the general conception. And similarly I can represent P B with capital P y B and now I will put this P B as well as P A in this equation.

So, when I do this I can find alpha should be equal to y A, x B divided by y B x A. So, in this way I can relate relative volatility with the composition of component in vapour phase as well as in liquid phase. So, let us see further I can rearrange this equation and find this new equation which should be equal to y A – y B and that should be equal to alpha x A / x B. So, if you consider this term as well as this term this I can represent simply by this where alpha is the relative volatility of component A with respect to component B because component B I have taken as the reference component.

And similarly when we consider this equation for this term it should be alpha BB x B / x B. So, that is basically 1 because when I consider relative volatility of a component with having the same reference so that should be 1 only. And similarly y C and y B I can represent by this considering this conception only. So, in this way I can represent the equation y A and y B + number of term should be equal to 1 / y B with this complete expression.

So, further I can obtain this term. Now how I will obtain this term? So, if you see here I am having alpha AB into x A. If I take this x B here so that would be x B / y B and all these term I can sum up. And that should be summation alpha AB x A and similarly when I vary A I can have summation of other components also. So, further I can rearrange the expression and I can obtain y B should be equal to x B divided by summation alpha AB into x A.

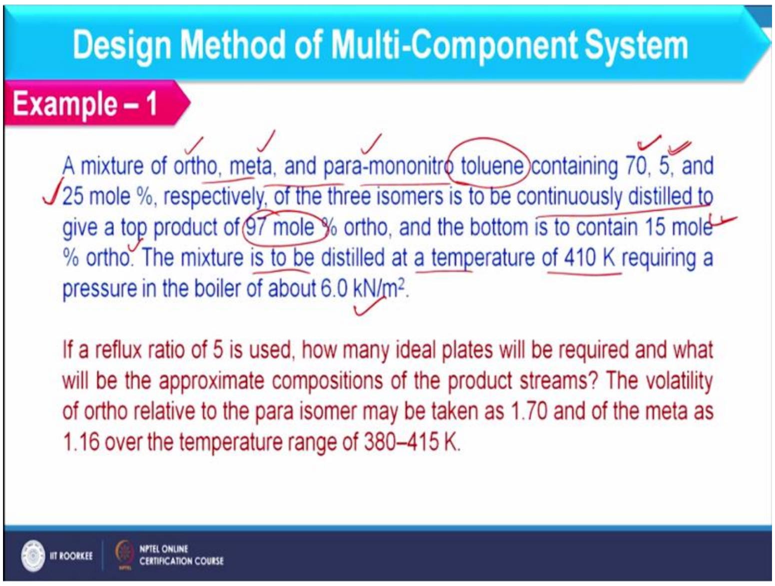
So, in this way composition of component B in vapour can be equated to composition of same component in liquid phase divisible by summation of relative volatility of component A with respect to B into x A. And similarly I can consider different components over here as we have discussed previously also and further we can consider y A should be equal to x A alpha AB divisible by summation of alpha AB x A.

Now, how I can obtain this equation? So, if you focus on this it is basically y A / y B which is equal to alpha x A / x B. If I consider y A from here that should be equal to alpha and this alpha should be AB x A and y B we can consider over here divisible by x B as it is available over here. Further, if I replace this y B with this equation what I can write alpha AB x A, x B divided by x B summation alpha AB x A.

So, this will be cancelled out and we can have this term which is available over here. So, in this way you can obtain the composition of y B with respect to other compositions. And similarly I can show the composition of component C in vapour phase and composition of component D in vapour phase. So, this equation we can calculate to find out the unknown composition in vapour phase if I know the composition in liquid phase.

Therefore, it considers that the composition of the vapour is conveniently found from that of the liquid by use of relative volatilities of the component as we have just seen. So, in this way you can see how we can obtain the composition in vapour phase if I know that in liquid phase. So, let us illustrate this method with the help of one example and here we have example 1.

**(Refer Slide Time: 15:36)**

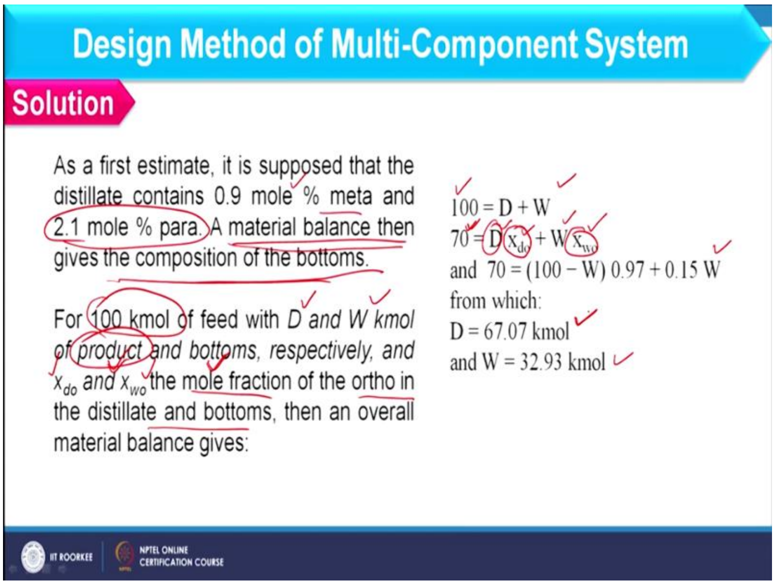



In this example a mixture of ortho, meta and para mononitro toluene which contain 70%, 5% and 25% mole in the feed and it is continuously distilled to give a top product where 97 mole percent of ortho and in the bottom 15 mole percent of ortho should be obtained. So, if I am having 97% ortho in the top product rest will be meta and para and this mixture is to be distilled at a temperature of 410 Kelvin which requires pressure in the reboiler about 6 kilonewton per meter square.

So, in this way composition in feed as well as some of the components in top products are given and further we are known that reflux ratio is 5. So, what we have to find is how many ideal plates will be required and what will be the approximate compositions of the product streams. The volatility of ortho relative to the para isomer maybe considered as 1.7 and that of meta as 1.16 in the temperature range 380 to 415 and 410 will be between this.

So, we can use this information to find out ideal number of trays using Lewis Matheson method. So, let us start that.

**(Refer Slide Time: 17:28)**



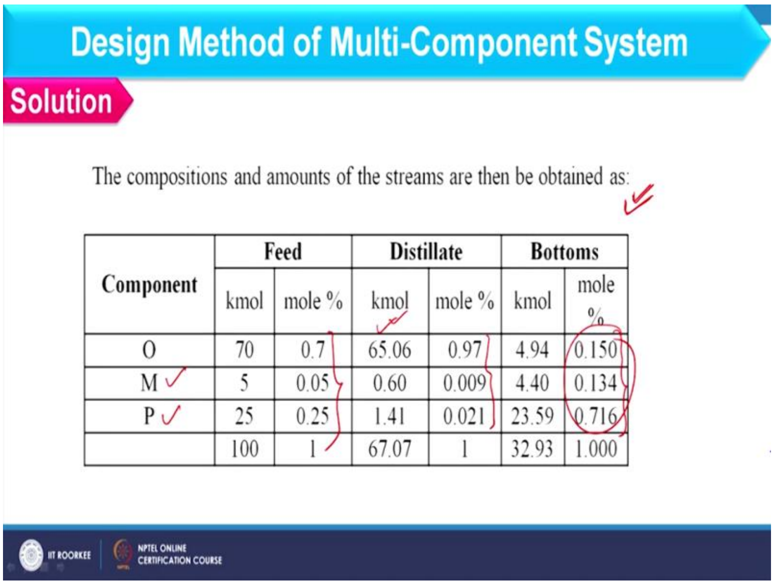

So, to start the calculation we will assume the unknown components in distillate. So, let us see how we can consider that. So, in the top we can consider that 0.9 mole percent meta and 2.1 mole percent para is available as feed contains only 5% as well as 25% of meta and para respectively. So, material balance will give the composition of the bottom product. So, let us see how to find it if I consider 100 kilomole of feed with D and W kilomole of product.

And bottom are available it means this product is basically the top. And composition is X d o and X w o which is basically the mole fraction of ortho in distillate and bottom. So, how I can find the component balance let us see that. So, you see overall balance should be 100 should be equal to D + W and then we can make the component balance based on ortho. So, ortho is 70% in the feed, total feed is 100 kilomole.

So 70 should be ortho and that should be equal to D into X d o + W into X w o. So, in distillate ortho is 97% and in bottom ortho is 15% it is already given to us. So, we can simply write the equation as 70 should be equal to 100 – W we can replace this D. This is the simple calculation into 0.97 + 0.15 into W. So, we can find out W from here as 32.93 and distillate as 67.07 kilomole.

So, once I know the flow rates or the total moles available in distillate and bottom I can make the balance on other components and complete the table for component available in feed, top and bottom.

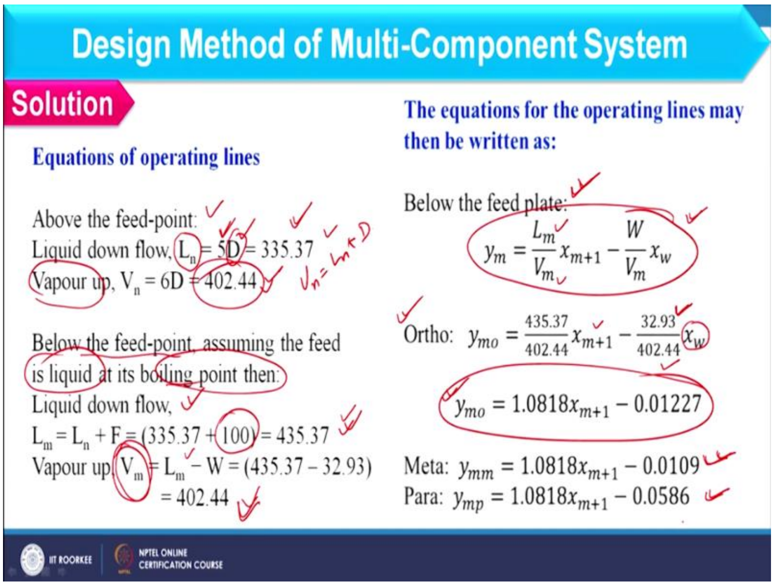
**(Refer Slide Time: 19:56)**




| Component | Feed | | Distillate | | Bottoms | |
|---|---|---|---|---|---|---|
| | kmol | mole % | kmol | mole % | kmol | mole % |
| O | 70 | 0.7 | 65.06 | 0.97 | 4.94 | 0.150 |
| M | 5 | 0.05 | 0.60 | 0.009 | 4.40 | 0.134 |
| P | 25 | 0.25 | 1.41 | 0.021 | 23.59 | 0.716 |
| | 100 | 1 | 67.07 | 1 | 32.93 | 1.000 |

So, in this table we can show the compositions of all components. So, feed it is already given, distillate we have assumed and bottom we can obtain by balancing. So, as we have done the balance on ortho in the similar line I can make the balance on meta as well as para. So, all these values you can obtain. Now, if you focus on Lewis Matheson method it basically calculates the composition of component considering operating line and the slope of this operating line. So, first of all we will see how the operating line of top and bottom can be obtained.

**(Refer Slide Time: 20:40)**




So, first of all we will focus on the above feed condition and there I can find out the liquid flow rate which is related to the reflux ratio as well as distillate. Distillate moles we know already and it should be multiplied by 5 because 5 is the reflux ratio. So, total liquid which is coming down is 335.37. And similarly I can find the vapour which is going up by simple material balance that V n should be equal to L n + D.

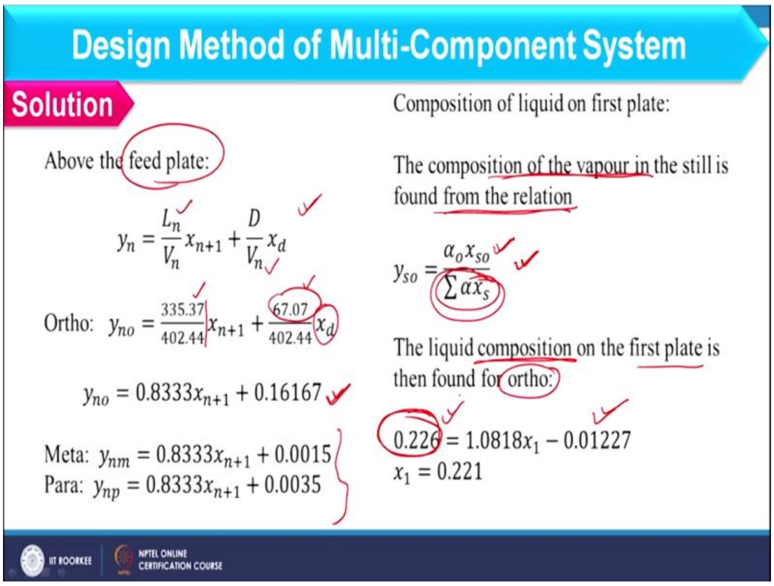
So, that should be 402.44. Further, what I consider is that below the feed point feed is available at boiling point. So, it is available in pure liquid. So, liquid which is coming down should be equal to whatever liquid is coming from the top that is 335.37 plus that is available with feed. So, total Lm which is coming down to the feed tray should be 435.37. In the similar line whatever vapour is going up below feed tray that should be equal to L m – W.

So, it is basically 402.44 that you can consider here as well. So, in this way we can find out the flow which is available above the feed as well as below the feed and now we will derive the expression for operating line. So, let us first focus on the bottom feed plate. If we consider the plate which is available below feed plate this is the expression. This we can consider in binary system also there we have derived it.

So, you can refer that lecture. So, if I focus on ortho than y m o is basically given by L m V m because it is below feed so L m should be this one and V m should be this one. It is multiplied by x m + 1 – W is basically 32.93 we have obtained that in the last slide and V m is basically 402.44 and that should be multiplied by x w. So, we can simply consider the equation for ortho as this.

So, this is basically the operating line below feed for component ortho. In the similar line I can consider the equation for meta as well as para as you can see here. So, considering these equations we can find out the composition of component at below feed plates.

**(Refer Slide Time: 24:17)**




Further, we consider above feed plates and this is the operating condition for that L n and V n I have already calculated in the previous slides so that you can refer. So, these values multiplied by x n + 1 + D / V n. So, D I have represented as 67.07 and V n I have obtained as 402.44 into x d. So, this is basically the operating line for ortho above feed plates and similarly I can obtain for rest two components.

So, let us start to calculate the composition in different plates. We will start with the first plate, but that first plate we are considering from the bottom. So, the composition of vapour we can find with the correlation related to composition of that component in liquid stream and relative volatility. So, this expression we have already derived previously that you can refer.

So, we can consider the liquid composition in first plate and that is for the component ortho and you can obtain this equation. So, this is basically bottom operating line and here I am having this value of y. So, how I can obtain this? Let us see this first.

**(Refer Slide Time: 26:00)**

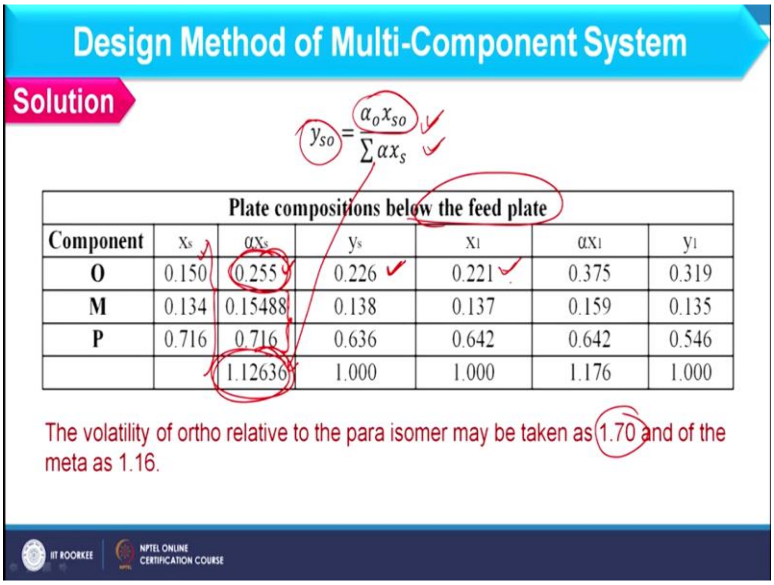


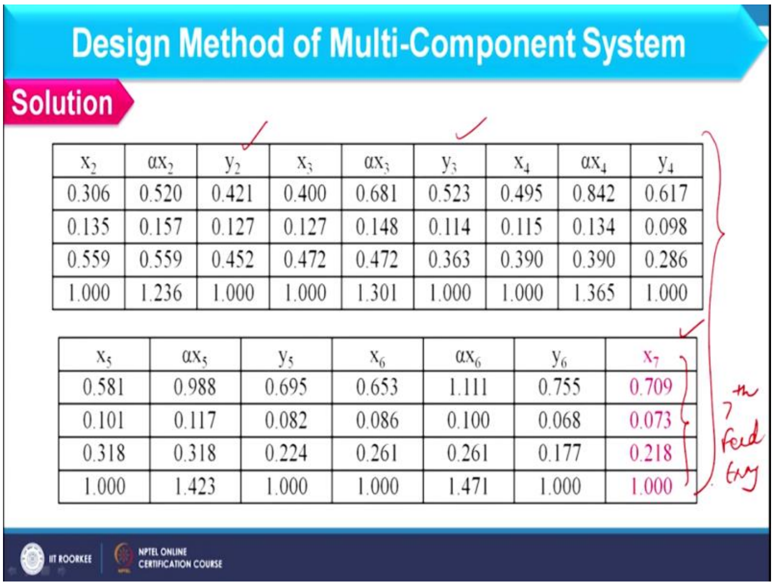

Plate compositions below the feed plate

| Component | $x_s$ | $\alpha x_s$ | $y_s$ | $x_1$ | $\alpha x_1$ | $y_1$ |
|---|---|---|---|---|---|---|
| O | 0.150 | 0.255 | 0.226 | 0.221 | 0.375 | 0.319 |
| M | 0.134 | 0.15488 | 0.138 | 0.137 | 0.159 | 0.135 |
| P | 0.716 | 0.716 | 0.636 | 0.642 | 0.642 | 0.546 |
| | | 1.12636 | 1.000 | 1.000 | 1.176 | 1.000 |

If you see the plate composition below feed we can obtain using this equation. And here I am having the composition of bottom plate this we have already seen previously. So, if you consider for ortho the composition is given as 0.15 and that we can multiply with relative volatility because here I have to consider that and relative volatility is given as 1.7. So, multiplication of 1.5 into 1.7 will give 0.255. And similarly I can obtain alpha X s as these.

Summation of this will give the value like this which is basically this value. So why how you can obtain simply divide this by this as you can see in this expression. So, 0.226 we can obtain which you can see over here. Considering this we can obtain x a as 0.221 as you can see here. So, in this way we can find out composition of each plate like first, second, third in that way.

**(Refer Slide Time: 27:29)**




| $x_2$ | $\alpha x_2$ | $y_2$ | $x_3$ | $\alpha x_3$ | $y_3$ | $x_4$ | $\alpha x_4$ | $y_4$ |
|---|---|---|---|---|---|---|---|---|
| 0.306 | 0.520 | 0.421 | 0.400 | 0.681 | 0.523 | 0.495 | 0.842 | 0.617 |
| 0.135 | 0.157 | 0.127 | 0.127 | 0.148 | 0.114 | 0.115 | 0.134 | 0.098 |
| 0.559 | 0.559 | 0.452 | 0.472 | 0.472 | 0.363 | 0.390 | 0.390 | 0.286 |
| 1.000 | 1.236 | 1.000 | 1.000 | 1.301 | 1.000 | 1.000 | 1.365 | 1.000 |

| $x_5$ | $\alpha x_5$ | $y_5$ | $x_6$ | $\alpha x_6$ | $y_6$ | $x_7$ |
|---|---|---|---|---|---|---|
| 0.581 | 0.988 | 0.695 | 0.653 | 1.111 | 0.755 | 0.709 |
| 0.101 | 0.117 | 0.082 | 0.086 | 0.100 | 0.068 | 0.073 |
| 0.318 | 0.318 | 0.224 | 0.261 | 0.261 | 0.177 | 0.218 |
| 1.000 | 1.423 | 1.000 | 1.000 | 1.471 | 1.000 | 1.000 |

So, when we see all compositions you can see the calculations over here. Now, further if we consider 2nd plate, 3rd plate and so on and the 7th plate you can find that 7th plate compositions are almost equal to that of feed. It means 7th should be the feed tray.

**(Refer Slide Time: 28:00)**

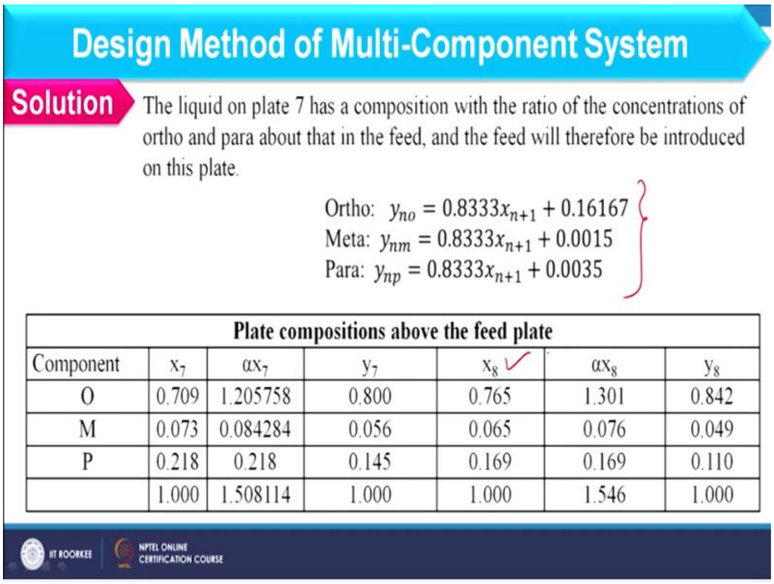
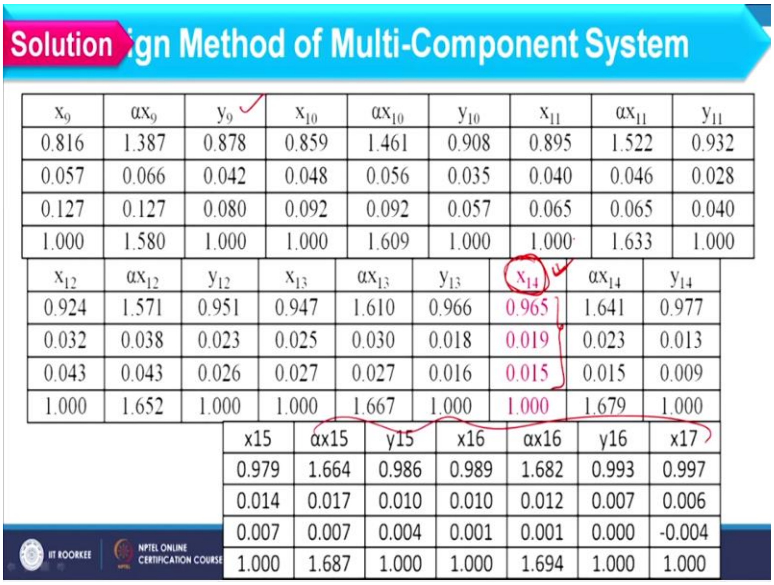



Plate compositions above the feed plate

| Component | $x_7$ | $\alpha x_7$ | $y_7$ | $x_8$ | $\alpha x_8$ | $y_8$ |
|---|---|---|---|---|---|---|
| O | 0.709 | 1.205758 | 0.800 | 0.765 | 1.301 | 0.842 |
| M | 0.073 | 0.084284 | 0.056 | 0.065 | 0.076 | 0.049 |
| P | 0.218 | 0.218 | 0.145 | 0.169 | 0.169 | 0.110 |
| | 1.000 | 1.508114 | 1.000 | 1.000 | 1.546 | 1.000 |

So, from the bottom we can reach to the feed tray and that is basically 7th tray. Now, we will consider the plates above the feed plate and that you can calculate using these operating lines which we have derived previously. So, in the similar line you can find the composition of 8th plate.

**(Refer Slide Time: 28:24)**




| $x_9$ | $\alpha x_9$ | $y_9$ | $x_{10}$ | $\alpha x_{10}$ | $y_{10}$ | $x_{11}$ | $\alpha x_{11}$ | $y_{11}$ |
|---|---|---|---|---|---|---|---|---|
| 0.816 | 1.387 | 0.878 | 0.859 | 1.461 | 0.908 | 0.895 | 1.522 | 0.932 |
| 0.057 | 0.066 | 0.042 | 0.048 | 0.056 | 0.035 | 0.040 | 0.046 | 0.028 |
| 0.127 | 0.127 | 0.080 | 0.092 | 0.092 | 0.057 | 0.065 | 0.065 | 0.040 |
| 1.000 | 1.580 | 1.000 | 1.000 | 1.609 | 1.000 | 1.000 | 1.633 | 1.000 |

| $x_{12}$ | $\alpha x_{12}$ | $y_{12}$ | $x_{13}$ | $\alpha x_{13}$ | $y_{13}$ | $x_{14}$ | $\alpha x_{14}$ | $y_{14}$ |
|---|---|---|---|---|---|---|---|---|
| 0.924 | 1.571 | 0.951 | 0.947 | 1.610 | 0.966 | 0.965 | 1.641 | 0.977 |
| 0.032 | 0.038 | 0.023 | 0.025 | 0.030 | 0.018 | 0.019 | 0.023 | 0.013 |
| 0.043 | 0.043 | 0.026 | 0.027 | 0.027 | 0.016 | 0.015 | 0.015 | 0.009 |
| 1.000 | 1.652 | 1.000 | 1.000 | 1.667 | 1.000 | 1.000 | 1.679 | 1.000 |

| x15 | αx15 | y15 | x16 | αx16 | y16 | x17 |
|---|---|---|---|---|---|---|
| 0.979 | 1.664 | 0.986 | 0.989 | 1.682 | 0.993 | 0.997 |
| 0.014 | 0.017 | 0.010 | 0.010 | 0.012 | 0.007 | 0.006 |
| 0.007 | 0.007 | 0.004 | 0.001 | 0.001 | 0.000 | -0.004 |
| 1.000 | 1.687 | 1.000 | 1.000 | 1.694 | 1.000 | 1.000 |

And 9th plate and so on. Now, if you consider the 14th plate in this case the composition will be more or less equal to whatever you can obtain in distillate. It is not exactly equal to, but it will be near to that. However, it is not possible when I am considering tray more than that.

So, what is the conclusion that total number of trays we can obtain as 14. So, in this way you can see how this method that is Lewis Matheson method works.

But it is very complicated as far as calculations are concerned. So, in the next lecture we will discuss some other methods to find out number of trays for multi component system. So, that is all for now. Thank you.