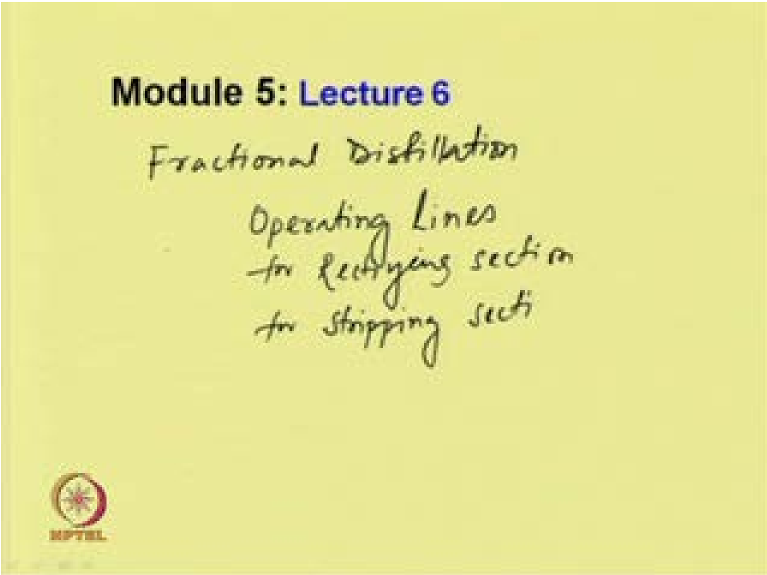
Mass Transfer Operations I
Prof. Bishnupada Mandal
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

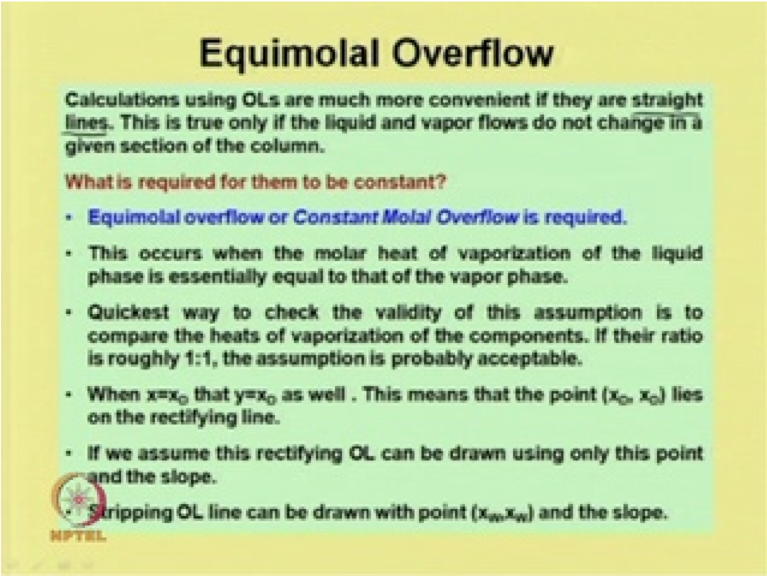
Module - 5
Distillation
Lecture - 6
Fractional Distillation:
McCabe Thiele Method

(Refer Slide Time: 00:29)



Welcome to the sixth lecture of module 5, module 5, we are discussing distillation. And in our previous lecture, we have started with fractional distillation. And we have learned how to operate the fractional distillation, and how to obtain operating lines, operating lines for rectifying section and for stripping section.

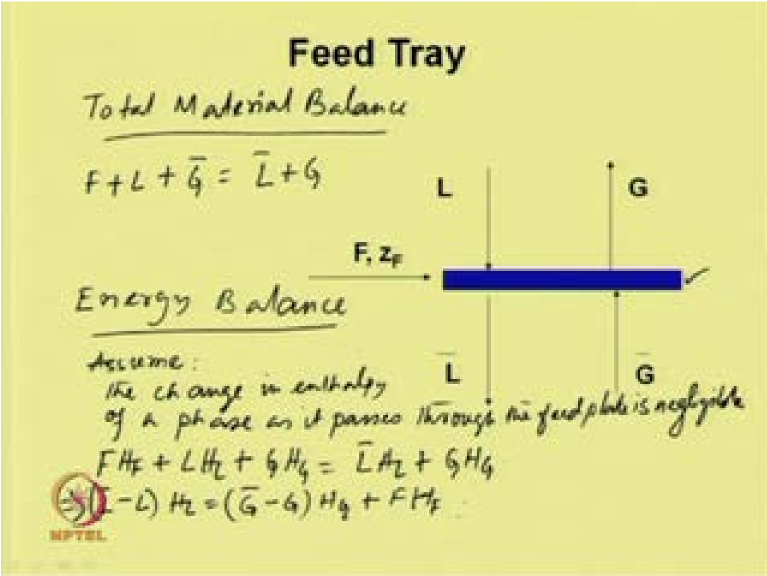
(Refer Slide Time: 01:29)



Today, we will continue with our lecture of fractional distillation. We will first discuss the Equimolal overflow. Our distillation calculation to obtain the number of plates would be much easier, if the operating line are straight lines. And this is true only when the liquid and the vapor flows among the rectifying sections and the stripping sections do not change. Then this line operating line for rectifying section and operating line for the stripping section should be straight line.

So, what is then required this flow in both the sections be constant that is required Equimolal overflow or constant molar overflow, which is required. And these conditions, the constant molar overflow happens when the molar heat of vaporizations of the liquid is essentially equal to the vapor. So, the quick way to check the validity of this assumption is to compare the heat of vaporizations of the components. If the heat of vaporizations of the components ratio is 1 is to 1, roughly 1 is to 1 then we say that the assumption is acceptable. So, when the flow is Equimolal in that case we can see that at x is equal to x d, y should be y d. So, the rectifying section line should pass the point x d and x g. It will be easy to plot the operating line with the slope of the operating line, and the point x d and x d. Similarly, for stripping section, if we know the slope, the stripping section we would start at the bottom composition of x w x w, and with the slope we can plot the operating line for the stripping section.

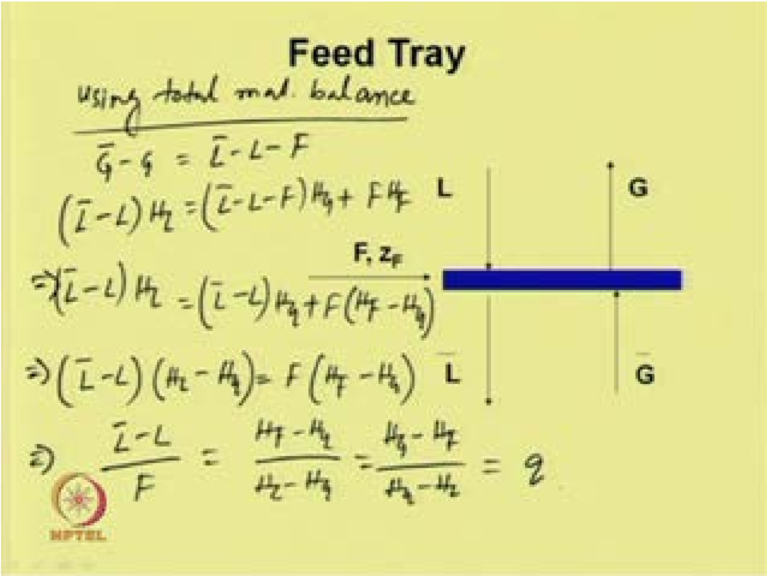
(Refer Slide Time: 04:03)



Now, we will discuss feed tray. Let us examine the steady state material balance on the feed tray. Consider this is the feed tray, where the feed which is coming with a composition of Z F and liquid, which is coming down below the feed tray is L bar. Liquid which is coming from the top section is L, liquid which is going to the feed tray is G bar, and which is coming out from the feed tray is G. So, if we write the total material balance F plus L plus G bar should be equal to L bar plus G. Now we will write the energy balance, energy balance.

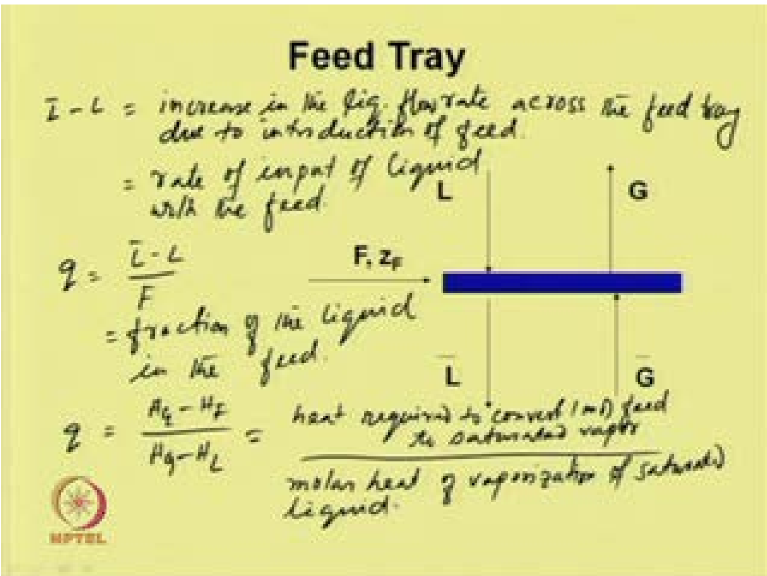
We know that in the energy balance, if we assume the change in enthalpy of a phase as it passes through the feed plate is negligible. So, if it is negligible, the change in enthalpy when phase passes through the feed plate then we can write the energy balance equation F H F plus L H L plus G H G is equal to L bar H L plus G H G. So from this, we can write L bar minus L into H L would be equal to G bar minus G H G plus F H F.

(Refer Slide Time: 07:00)



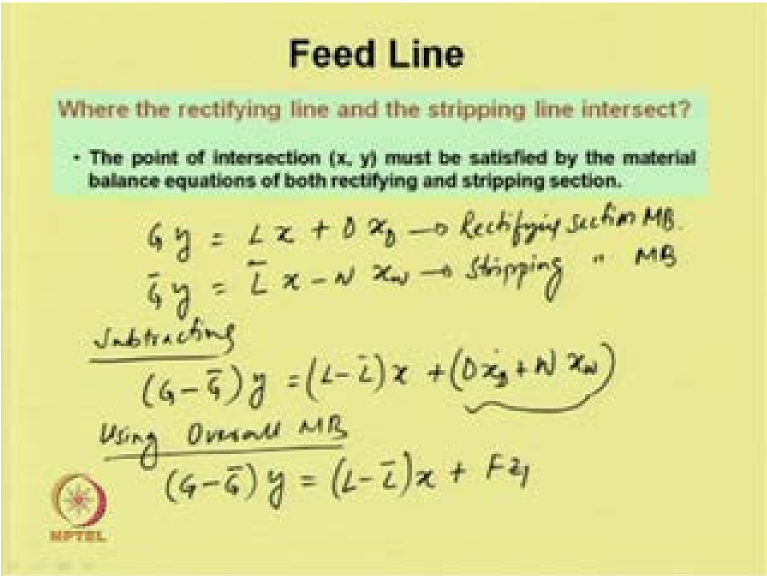
Now if we use the total material balance in this equations we will get G bar minus G is equal to L bar minus L minus F. So, if we substitute the energy balance equation would be L bar minus L into H L is equal to L bar minus L minus F H G plus F H F. So, if we just simplify, L bar minus L H L would be equal to L bar minus L H G plus F into H F minus H G. So, we can write L bar minus L into H L minus H G would be equal to F into H F minus H G. So, then we can write L bar minus L by F should be equal to H F minus H G divided by H L minus H G is equal to H G minus H F divided by H G minus H F, which we can say a quantity q.

(Refer Slide Time: 09:05)



Now this L bar minus L, this is the increase in the liquid flow rate, liquid flow rate across the feed tray. So, across the feed tray due to introduction of feed. So, then this we can say the rate of input of liquid, input of liquid with the feed. So, we can write q is equal to L bar minus L by F is the fraction of the liquid in the feed. Again, we can write q is equal to H G minus H F divided by H G minus H L, which we can write heat required to convert one mol feed to saturated vapor divided by molar heat of vaporization of saturated liquid.

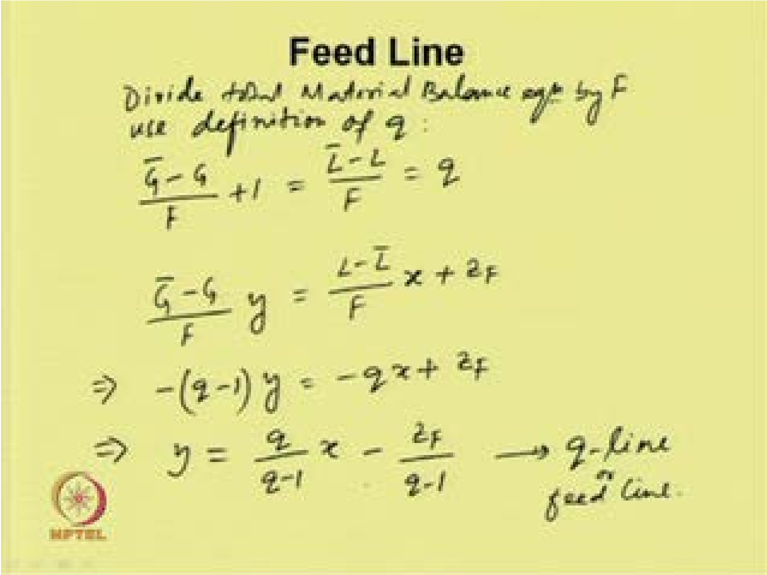
(Refer Slide Time: 11:47)



Now it will be interesting to know the feed line its location. So, where the rectifying section line and the stripping section line intersect at what location. So, that is very important for the calculations of the number of plate in the fractional distillation. The point of intersection which is x y must be satisfied by the material balance equations of both rectifying and stripping section.

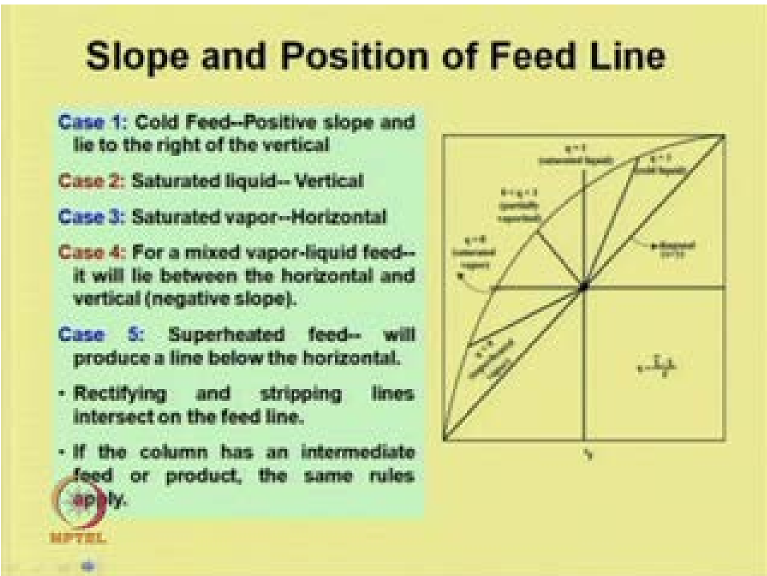
Let us do the material balance equations both the sections as we have done before. G y is equal to L x plus D x D and G bar y is equal to L bar x minus W x W this is the rectifying section, material balance and this is stripping section. Now subscribe the rectifying section equations from the stripping section equations. We will get G minus G bar into y would be equal to L minus L bar into x plus D x D plus W x W. Now if we use the overall material balance equations, we would obtained G minus G dash into y would be equal to L minus L bar into x plus F. So, this part is F z f.

(Refer Slide Time: 14:34)



If we divide the total material balance equations by F and use definition of q. Then we would get G bar minus G by F plus 1 is equal to L bar minus L by F is equal to q. And now if we take this relation, so it would be G bar minus G divided by F into y is equal to L minus L bar by F into x plus z F. So, if we use this relation, it will be minus q minus 1 into y is equal to minus q x plus z F. So, from this we will get y is equal to q by q minus 1 x minus z F by q minus 1. So, this is another operating line in addition to the two operating lines we have obtained earlier for stripping section and the rectifying section. This is called the feed line or q line.

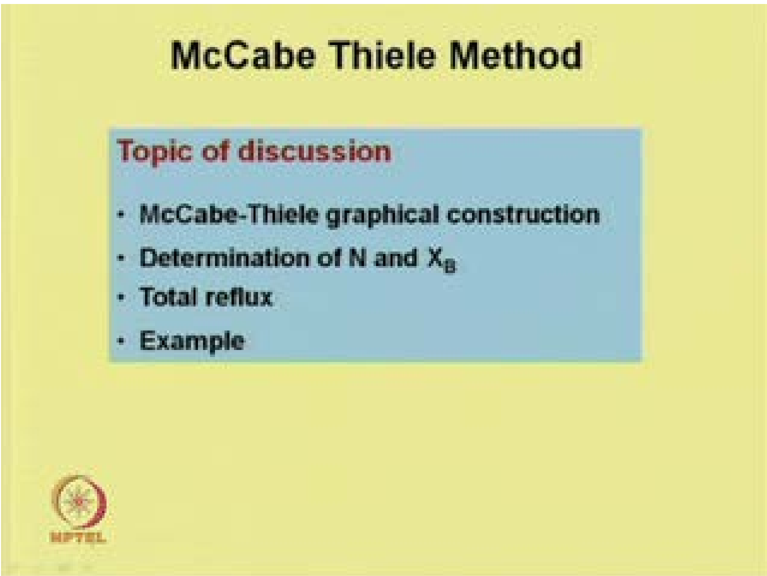
(Refer Slide Time: 17:03)



Now, it would be interesting to know the locations with this q line or feed line equations. As we have discussed before, there are different kinds of feed conditions we can use. If we considered feed as a cold feed then the slope you can see q would be equal to L bar minus L y F. So, the slope would be positive and it will lie to the vertical line, since q is grater then one. Now in case of saturated liquid where q would be one. So, the operating line or q line should be vertical. The third case were the feed is saturated vapor, so in that case, the q would be L bar minus L by F which is horizontal in nature; q would be 0. So, the operating line or q line would be horizontal.

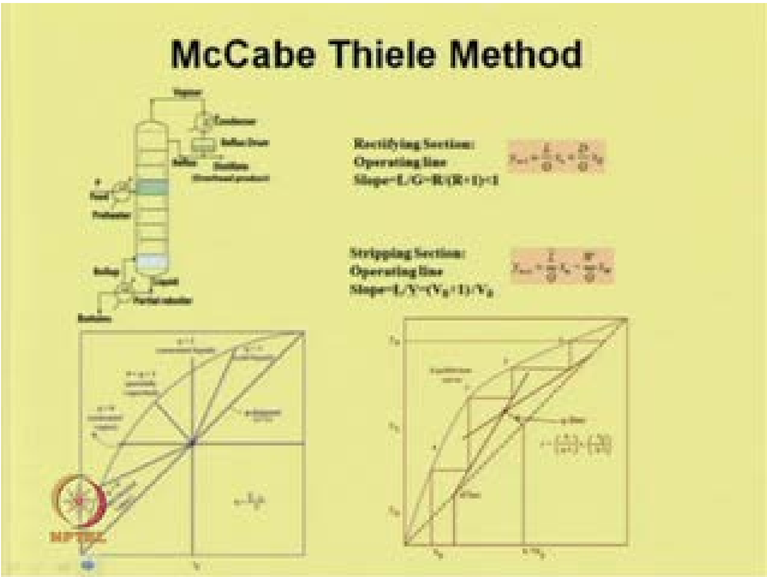
For a mixed vapor liquid feed, the slope would be negative. It is less than 0, because of negative slope, it will be below the horizontal line. Now if feed is mixture of vapor and liquid, in that case the slope is negative and the value of q lies between 0 and 1. So, q is greater than 0 and less than 1. So, it will lie between the vertical and the horizontal line now if feed is which is superheated vapor in that case value of q is less than 0. So, the line will lie below the horizontal line. The rectifying section line and the stripping section line will pass through the intersect through the feed line. So, feed line should pass through the intersection points of the stripping section line operating lines and the operating line of the rectifying section. So, if the column has an intermediate feed or product the same rule apply.

(Refer Slide Time: 19:11)



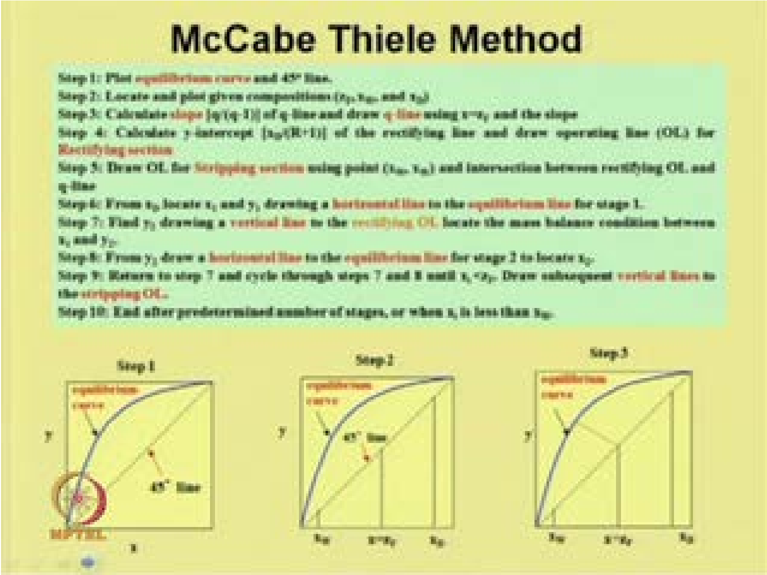
Now we will discuss the distillation calculation. So, there are assumptions we have done before that is the Equimolar overflow, if the Equimolar overflow as we discussed at the binging if that is apply in that case the operating line of stripping section and the rectifying section is straight line. And in that case the graphical method of McCabe-Thiele can be used to obtain the number of ideal plates required. Or, if the Equimolar over flow cannot be assume, in that case we have to use the energy balance equations in conjunction with material balance equations. So, the method which we follow is the Ponchon and Savarit method. So, today we will discuss the McCabe-Thiele method of analysis how to determine the number of plates and the mole fractions in the liquid phase and then the total reflux the limiting cases we will discuss with an example.

(Refer Slide Time: 20:28)



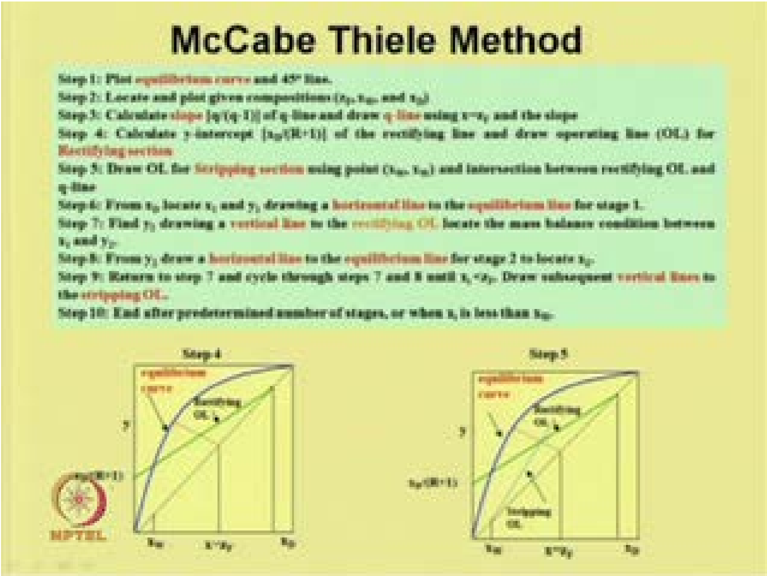
As we discussed before, this is the trade distillation column, where we have single feed and that condenser, and there is a reflux and only one product outlet and one overhead product and one-bottom product and there is no other sight curve. So, we know the operating line equations, so this is L bar by G the slope G bar and this is G w and G w. As we discussed before, the locations or the feed line or the q line, how it will vary in different situations for different feed condition. How to obtain the operating line we have discussing for both the sections, we will discuss how to obtain the number of theoretical stages required using graphical method and theoretical method.

(Refer Slide Time: 21:39)



So, in case of graphical constrictions for McCabe-Thiele is generally used for constant molar overflow. The procedure we follow first plot the equilibrium curve and the 45 degree line diagonals, which is shown over here. We know the equilibrium data, so the y x and y we can plot. So, this is the equilibrium line, the blue line indicates the equilibrium line, and 45 degree diagonal. Then we have to locate the feed conditions and the distillate overhead and the bottom conditions for the mole volatile components which are given x d Z F the feed compositions and x w which is the bottom compositions of the mole volatile components. So, this points are located and then this should be plotted calculate slope of q line q y q minus 1 this is the slope of the q line and draw the q line using x is equal to Z F that is the feed conditions. So, at x is equal to Z F, this the q line. As soon as the q line is plotted, now we will calculated the y line intersect. So, how to we calculate we located the point at x d on the 45 degree diagonal then we have to calculate x d by R plus 1, that is the rectifying section line and draw the operating line for this section.

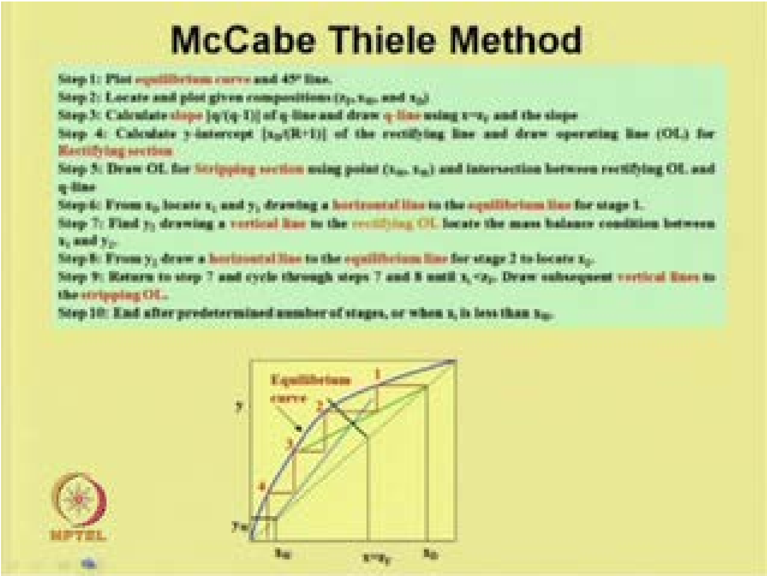
(Refer Slide Time: 23:49)



So we will see how to do that. We know this point, we know x d by R plus 1 x d is known to us, and the R is the recycle ratio or reflux ratio. So, if you know R and x d, we can calculate x d by R plus 1. We know this point and then we can plot the operating line between this two points.

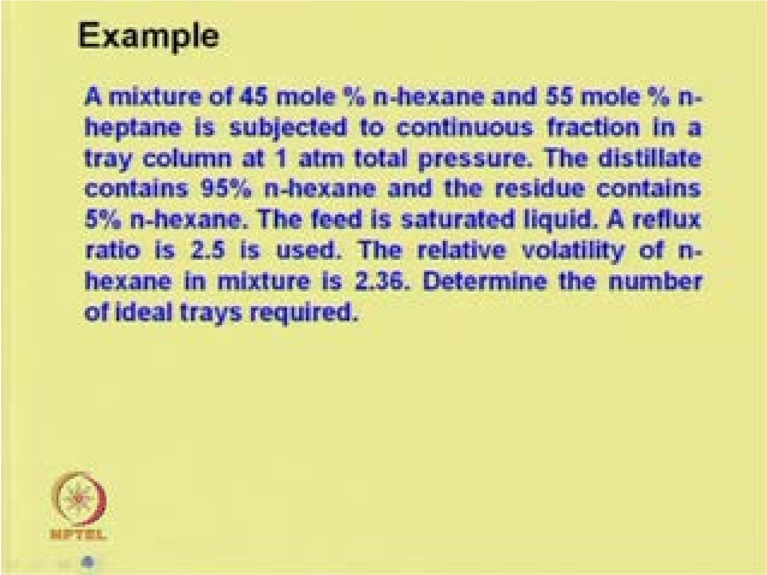
Now, draw the operating line for stripping section using x w x w, and the inter section between rectifying operating line and the q line. So, the q line and rectifying section line intersect at this point. This line is q line, so it intersects at this point and we know the bottom points x w from this point and the intersection point we can draw the operating line for the stripping section. So, we know both the sections operating line and the q line and this is the intersection point, which is the feed plate locations. Now we will calculate the number of plates requires by graphical method.

(Refer Slide Time: 25:03)



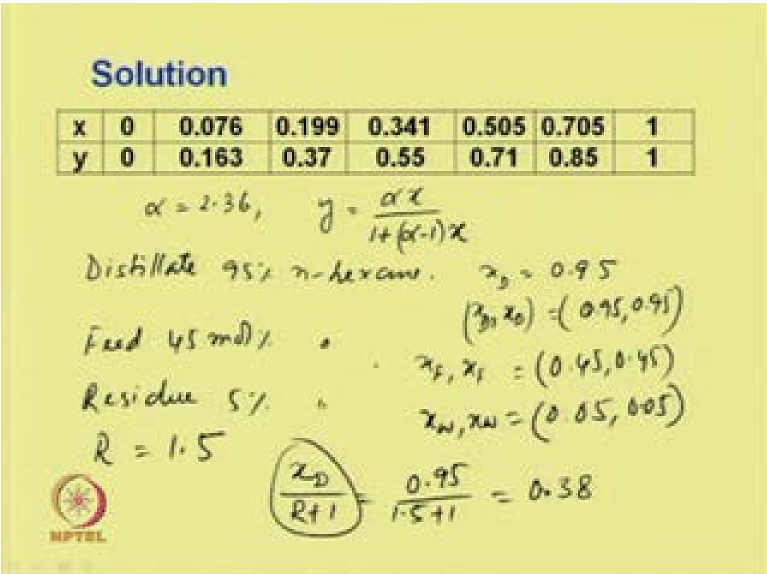
So, we will start at locations x d, we can start from any point either from the bottom or at the top of the tower. So, if you start at x d then from the x d locate x 1 and y 1 by drawing a horizontal to the equilibrium line for stage one. And then point y to from the equilibrium line to the vertical line on the rectifying section operating lines. So, we will plot from here to here horizontal line and then we will plot the vertical line, so this is for stage one. And then the same procedure we will follow from y to draw another horizontal line to the equilibrium line and then vertical line, so this should come here. So, this will give, this will give another stage and the same procedure we will follow until we reach x w or x w which is less then z F. So, when x i less than x w, we will stop it. This is number 1, number 2, number 3, number 4 four plates are required in this case.

(Refer Slide Time: 26:46)



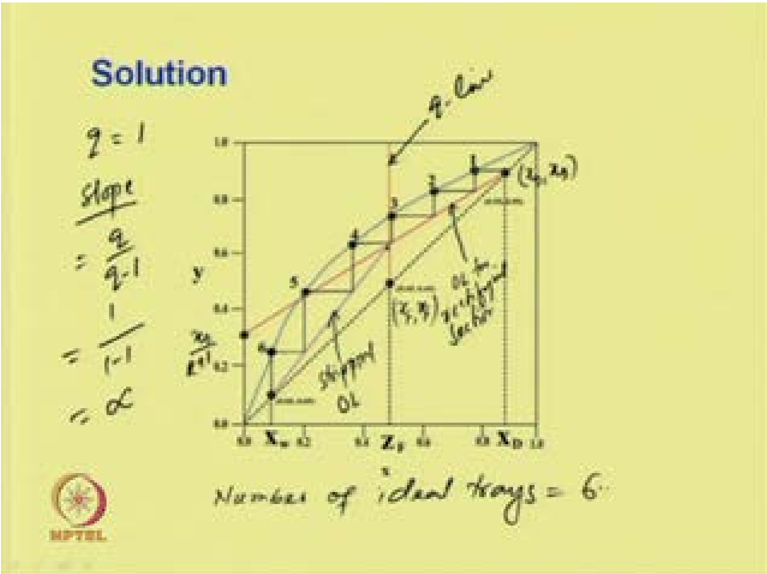
Let us take an example a mixture of 45 mole percent n-hexane and 55 mole percent n-heptane is subjected to continuous fractionation in a tray column at one atmosphere total pressure. The distillate contains 95 percent n-hexane and the residue contains 5 percent n-hexane. The feed is saturated liquid. A reflux ratio is 2.5 is used. The relative volatility of n-hexane in mixture is 2.36. Determine the number of ideal trays required.

(Refer Slide Time: 27:31)



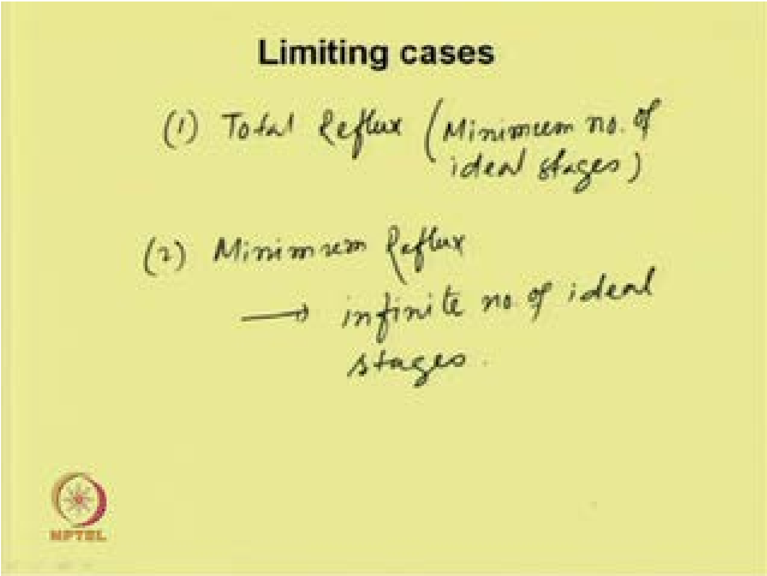
So, this is the similar problem as we discussed before. Given alpha values. Alpha is equal to 2.36, and we know the relation between y is equal to alpha x divided by 1 plus alpha minus 1 into x. So, if we take different x values and we can obtain y values using this alpha is equal to 2.3. So, this is the table which shows the equilibrium data. So, we can plot the equilibrium curve. Now the distillate contains distillate, which contains 95 percent n-hexane, so that means, x D is 0.95. We know the point x D, x D; this point is 0.95, 0.95. And feed has 45 feed, 45 mole percent n-hexane. So, x F, x F this point should be 0.45, 0.45 and then the residue is 5 percent n-hexane. So, x W x W this point is 0.05, 0.05. And the reflux ratio R is given 1.5. So, we can calculate x D by R plus 1 which is 0.95 divided by 1.5 plus 1 which is equal to 0.38, and we know the slope of the q line. So, this x D by R plus 1 this we know.

(Refer Slide Time: 30:11)



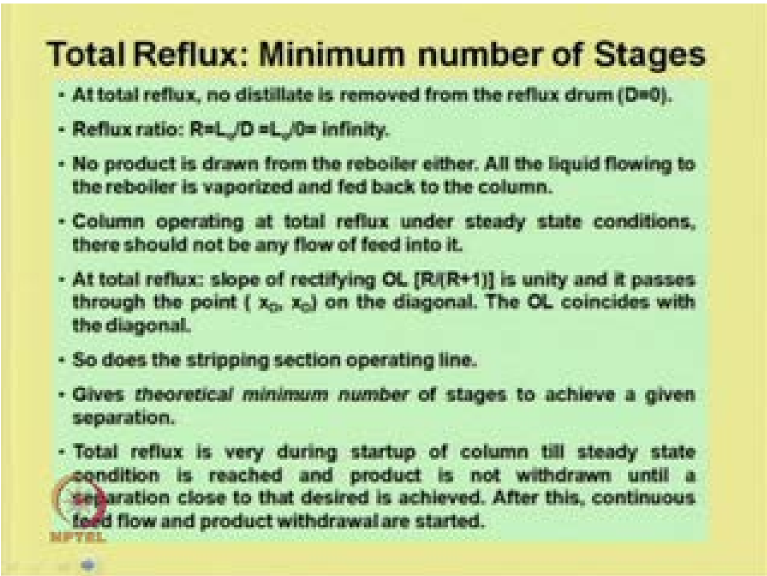
So, we know this is x D by R plus 1, and this point is known which is x D x D. Then with this point and with this point operating line for the rectifying section, we can plot. Similarly, we know x W, x W - 0.05, 0.05. So, before that the feed conditions which is given the feed is saturated liquid, so q is equal to 1. So, slope of the q line is equal to q by q minus 1 is equal to 1 by 1 minus 1 which is infinity. So, it will be a vertical line from this point at x F, x F, so this is the q line. So, we know the q line and we know the intersection point. So, using the x W, x W values and intersection point, we can plot the stripping operating line. Then the similar procedure, we start at the top of the column at x D and we draw a horizontal line to the equilibrium curve and then to the operating line then equilibrium curve and operating line, and if we do that the number of trays number of ideal trays is 6. So, 6 number of trays are required.

(Refer Slide Time: 32:18)



Now there are two limiting cases, in case of fractional distillations. One is the total reflux - total reflux, this gives minimum number of ideal stages. And second is the minimum reflux, so this gives the infinite number of ideal stages. In case of distillation design, there is a normal tread of between this reflux and stages. What reflux ratio we should use and what number of stages we required, there is a standard optimization problem. For which, we need to consider the cost parameter to obtain the optimum reflux ratio.

(Refer Slide Time: 33:49)

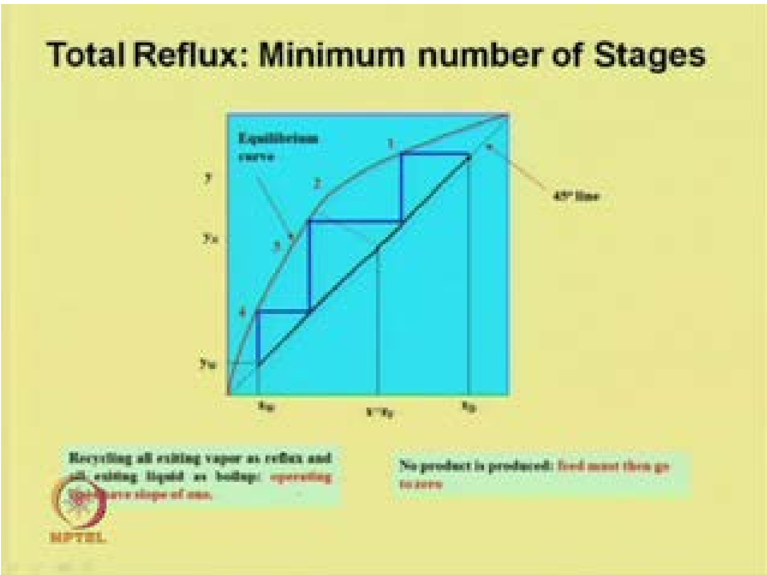


Today we will discuss the total reflux, where we will obtain the minimum number of stages. At total reflux, what happens all the vapor which will be condensed at the overheat reflux drum will be liquid and returned back to the column without taking any product, a without removing any product from the reflux drum. So in that case, the D the distillate would be 0 and the reflux ratio which is are L 0 by D would be infinity. So, no product is drawn from the reboiler either. So, all the liquid flowing to the Reboiler is vaporized and feedback to the column.

So, column which is operating at total reflux condition under steady state conditions, there should not be any flow of the feed into the column. So, we should not give any feed when the column will operate at total reflux. So at total reflux, the slope of the operating line O L R by R plus 1 is unity, and it passes through the x D, x D point and fall on the diagonal line. So, the operating line of the rectifying section coincides with the diagonal. Similarly, the operating line of the stripping sections also coincides with the diagonal.

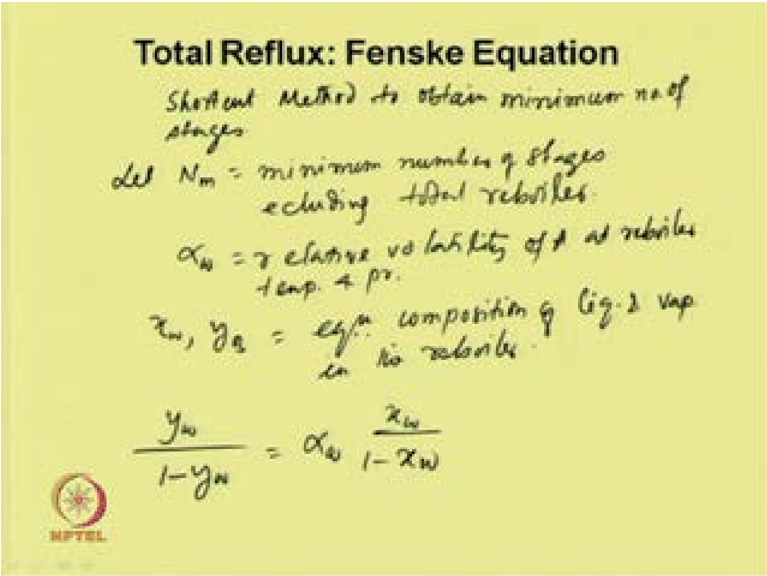
So, this situations at total reflux, it gives the minimum number of theoretical stages required to achieve a given separation. This total reflux is very common during the start up of the column till study state condition is reached. At the startup and the product is withdrawn until a separation close to the desired is achieved. And after this, we will continue feed flow to the column. So, we will see graphically how to obtain the minimum number of stages when there are total reflux in the column.

(Refer Slide Time: 36:06)



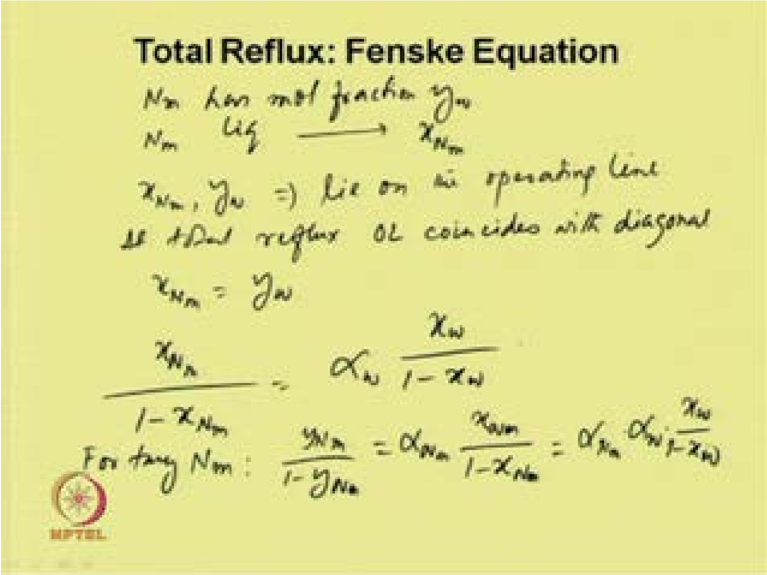
So, at this stage at total reflux, so both the operating line will lie on the, so this operating line for the rectifying section, and this is the operating line for the stripping section, so this will coincide. So, we can obtained we know x d and we will make the steer stage of operations as we did before. So, it will give the minimum number of stages required for the operation.

(Refer Slide Time: 36:40)



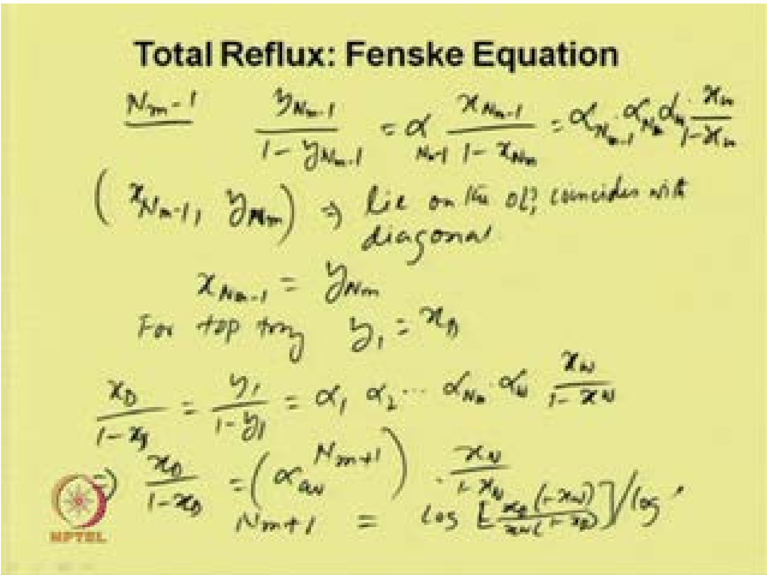
So, this is the graphical analysis now there is another method which is known as the Fenske equations which is a shortcut method, Fenske equation which is a shortcut method to obtain the minimum number of stages. So, there are so many approximate methods are available; it is one of them to obtain the minimum number of stages. Let N m be the minimum number of stages, minimum number of stages excluding total reboiler. Now alpha W is the relative volatility of A at reboiler, temperature, and pressure. Now x w and y w these are the equilibrium composition of liquid and vapor in the reboiler. Then we can write y w divided by 1 minus y w would be equal to alpha w x w by 1 minus x w. Now the vapor which is leaving the reboiler and entering the lowest tray that is N m has a mol fraction of y w and the liquid which is leaving N m, it has x N m.

(Refer Slide Time: 39:15)



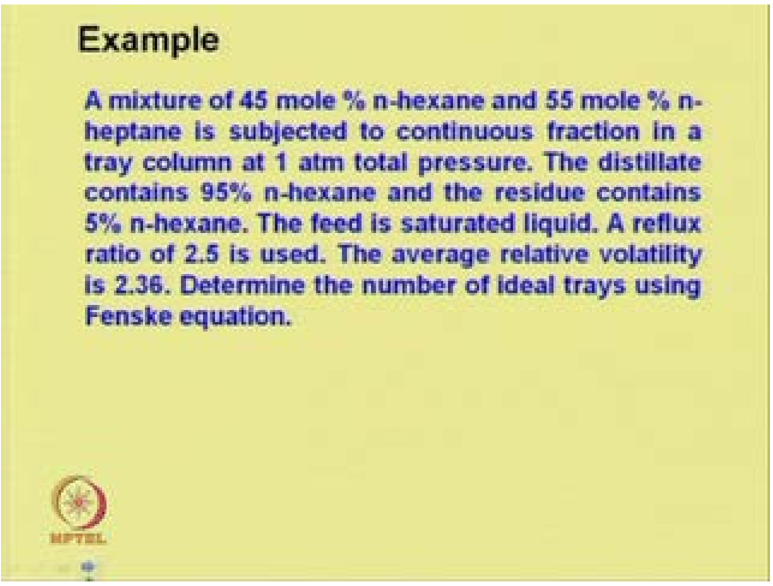
So, the point x N m and y w - this lie on the operating line. At total reflux operating line coincides with diagonal. So, x N m should be y w. So, if we put in that equations, it should be x N m by 1 minus x N m would be equal to alpha w x w divided by 1 minus x w. Applying the same procedure, we will obtain y N m divided by 1 minus N m would be equal to alpha N m x N m divided by 1 minus x N m. So, if we apply for tray N m, so we can write alpha N m into alpha w into x w divided by 1 minus x w.

(Refer Slide Time: 41:32)



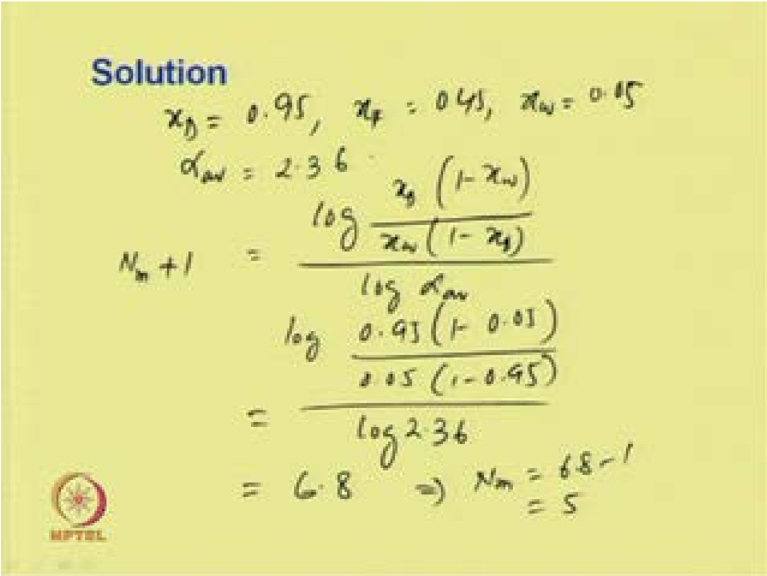
Similarly, if we apply same thing, in case of N m minus one, we would be obtain y N m minus 1 divided by 1 minus y N m minus 1 is equal to alpha x n m minus 1 divided by alpha. This will be N N m minus 1 divided by 1 minus x n m is equal to alpha N m minus 1 into alpha N m alpha w into x w divided by 1 minus x w. So, the point x N m minus 1 and y N m this point lie on the operating line and coincides with diagonal. Therefore, in this case, we can write x N m minus 1 would be y N m. So, if you continue same procedure for the top tray, y 1 is equal to x dif we include that we can write x d by 1 minus x d would be equal to y 1 divided by 1 minus y 1 would be equal to alpha 1 alpha 2 and so on alpha N m into alpha w x w divided by 1 minus x w. So, from this we can write x d by 1 minus x d is equal to alpha average to the power N m plus 1 into x w by 1 minus x w. So, from this we can write N m plus 1 should be equal to log of x d into 1 minus x w divided by x w into 1 minus x d divided by log alpha average.

(Refer Slide Time: 44:16)



Let us take a very simple example, same examples, which we have discussed before. A mixture of 45 mole percent n-hexane and 55 mole percent n-heptane, which is subjected to the fractionation at one atmosphere pressure. The distillate contains 95 percent n-hexane residue contains 5 percent n-hexane. The feed is saturated liquid. The reflux ratio of 2.5 is used. The average relative volatility is 2.36. Determine the number of ideal trays using Fenske equations.

(Refer Slide Time: 44:53)



So, the data which is given that is x D is 0.95, x F - 0.45, x W - 0.05, alpha average is 2.36. And we know N m plus 1 is equal to log of x D into 1 minus x W divided by x W 1 minus x D divided by log of alpha average. So, if we put the values, it is log of 0.95 into 1 minus 0.05 divided by 0.05 into 1 minus 0.95 divided by log of 2.36. So, this will give around 6.8. So from here, we can calculate N m is equal to 6.8 minus 1, which is equal to 5.8, almost same values we have obtained using the graphical method.

Thank you.