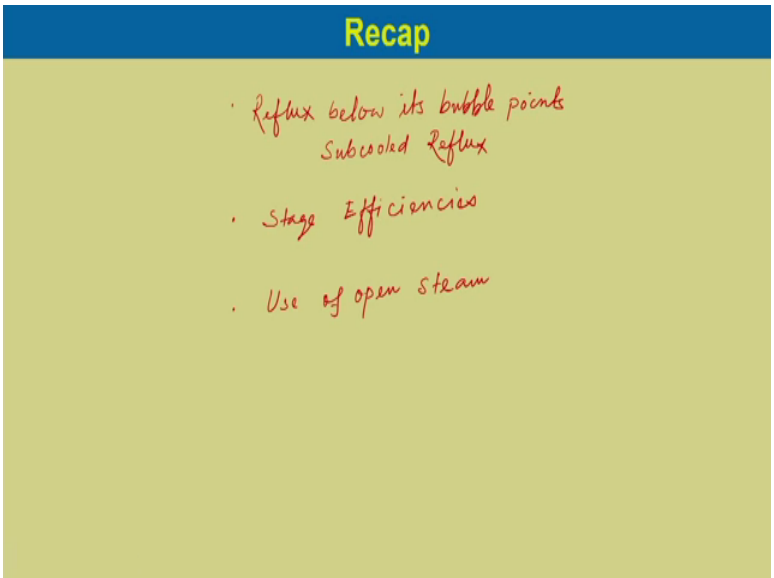
Mass Transfer Operations -I
Prof. Bishnupada Mandal
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Lecture – 34
Distillation

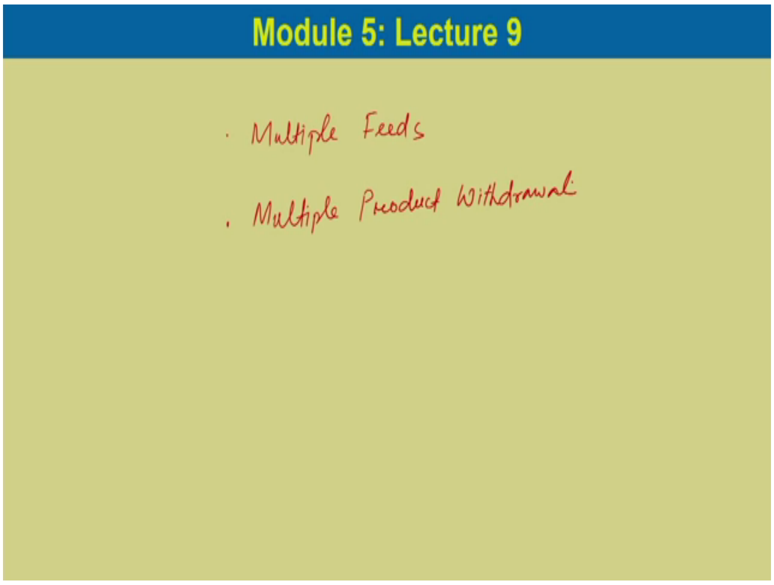
Welcome to 9th lecture of module 5 of Mass Transfer Operation. In this module we are discussing Distillation operation. Let us have small recap on our previous lecture before going to this lecture.

(Refer Slide Time: 00:57)



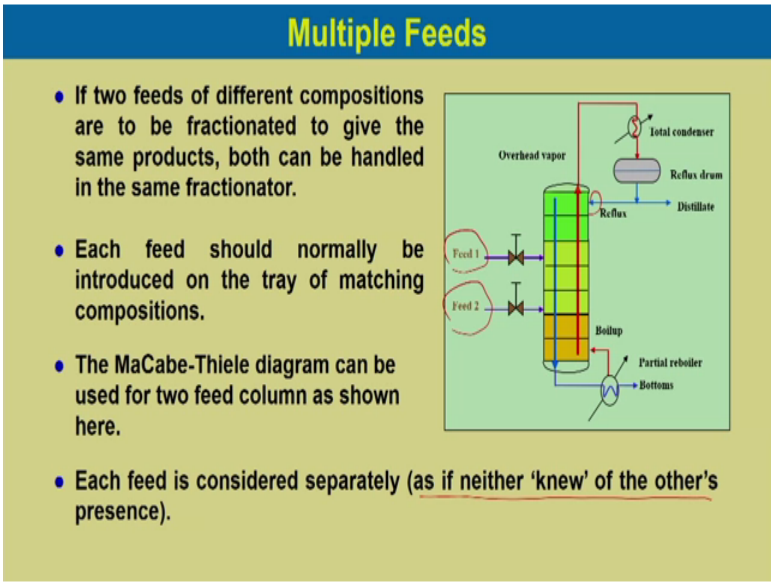
In our previous lecture, we have discussed three important topic. One is know reflux below its bubble point; that means, the reflux which is given to the top of tray of the column is subcooled reflux. The second thing we have discussed is different stage efficiencies and third thing we have discussed use of open steam for the distillation.

(Refer Slide Time: 02:00)



So, in this lecture we will considered two important thing, one is multiple feed and second thing we will consider, if we take multiple product output so, multiple product withdrawal. So, let us start with our discussion with multiple feeds.

(Refer Slide Time: 02:33)



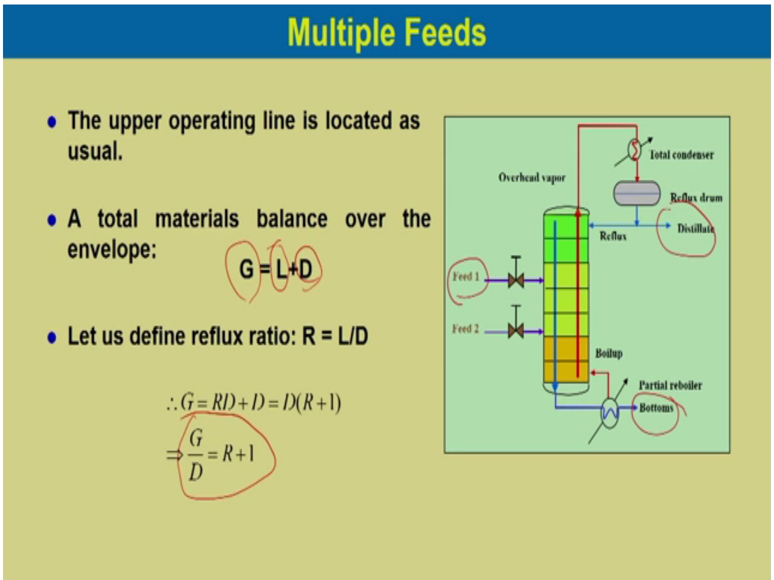
So, you can see over here in the distillation operations, we have feed 1 and feed 2. So, two different feed are given to the distillation column and we have single reflux in at the column and then as per the other design we have boiler at the bottom which have reboiler.

So, if two feeds of different compositions are to be fractionated to give the same products both can be handled in the same fractionator. So, the target is that we have two different composition feed and we want the same product composition outlet both the know bottom and top, then both the feeds can be accommodated in the same column. So, that is the purpose of the multiple feeds. Each feed should normally be introduced on the tray of matching composition.

So, depending on the composition because once the feed is introduce and it distributes throughout the column stage to stage both know stripping section as well as the rectifying section, and then the composition change. So, depending on the composition change the second feed will be introduced to the matching composition of the tray.

The McCabe- Thiele diagram can be used for two feed column as shown here. So, that know we will discuss later, we will use for this type of two feed column, we can use McCabe- Thiele type of diagram. Each feed is considered separately as if neither knew of the others presence.

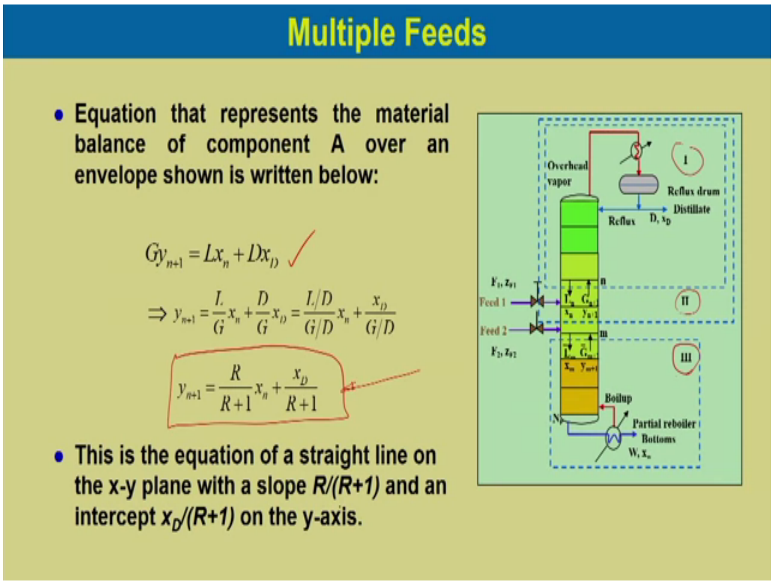
(Refer Slide Time: 04:27)



The upper operating line is located as usual, a total material balance over the envelope if we do. So, distillate which flow at the top of the column is G that is the gas inlet at the bottom of the tower and liquid which is coming out at the bottom and then the distillate which is going out at the top.

So, distillate, bottoms and the feed in. Let us define reflux ratio R is equal to L by D and if we do the balance, G is equal to RD plus D. So, we substitutes. So, in place of know L we can substitute RD. So, it will be D into R plus 1 from here G by D would be equal to R plus 1.

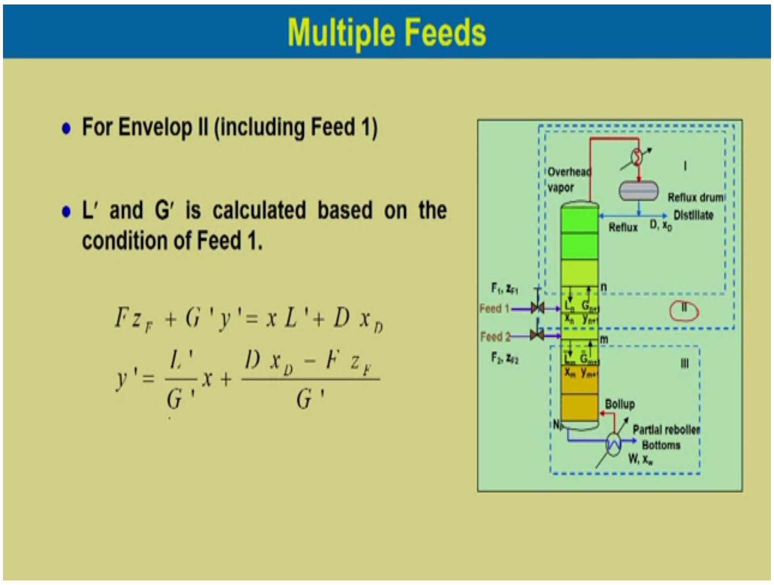
(Refer Slide Time: 05:27)



Now, equation that represents the material balance over and envelop shown over here, we have written over here three envelopes; envelope I, envelope II and envelope III. So, three envelopes let us do the balance equation for envelope 1. So, we have G into y n plus 1 would be equal to L into x n plus D into x D. So, from here know we can write y n plus 1 would be L by G into x n plus D by G into x D. So, it would be L by D by G by D x n plus x D by G by D and like in rectifying sections you have derive the equation for the operating line, that is y n plus 1 would be equal to R by R plus 1 into x n plus x D by R plus 1. So, this is based on the overall material balance or species mole balance in case of envelop I. So, we can get the operating line for the rectifying section for envelope I.

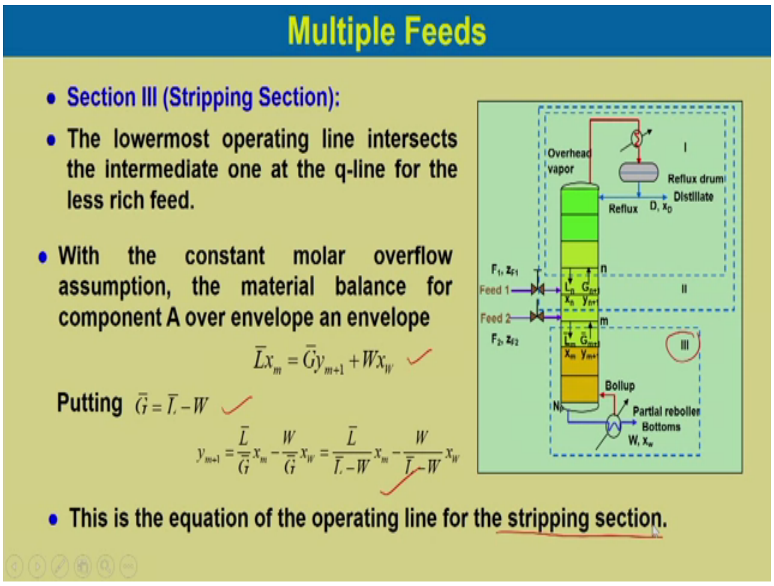
So, this is the equation of straight line on the x-y plane with a slope of R by R plus 1 and intercept of x D by R plus 1 on the y axis.

(Refer Slide Time: 07:00)



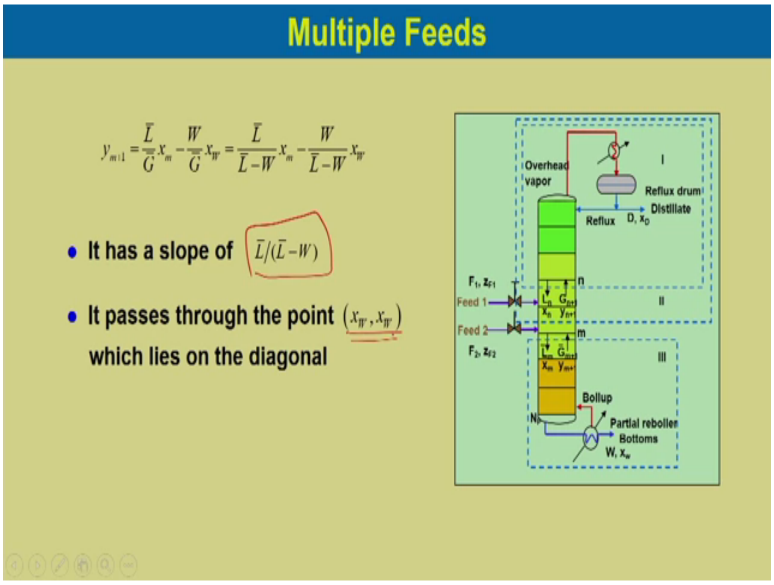
Now, for envelope II that is including feed 1. So, if we include feed 1 over here. So, that is the envelope II shown over here so, this is envelope II and we define in state of L and G we define in this case is L dash and G dash liquid and gas flow and each calculated on the condition of the feed 1. So, if we do the species mole balance F into z F plus G dash into y dash would be equal to x into L dash plus D into xD. So, from here we can write y dash would be equal to L dash by D dash into x plus D xD minus F z F by G dash.

(Refer Slide Time: 07:58)



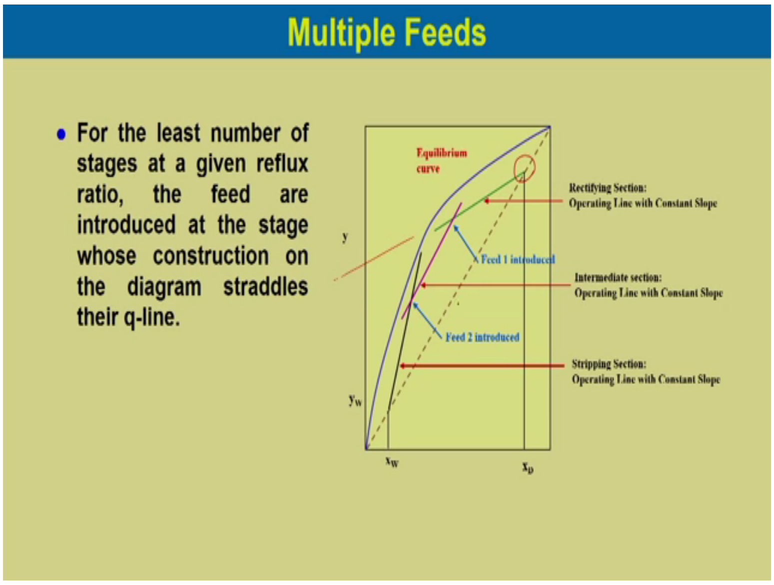
Now, if we take the other section that is envelope III which is the below the feed tray 2. The lowermost operating line intersects the intermediate one at the q-line for less rich feed. So, with the constant molar overflow assumptions the material balance for the envelope A over an envelope III, we can write L bar x m would be equal to G bar y m plus L plus W x W. So, now, we can put know G bar would be equal to L bar minus W as we have done for the stripping section earlier . So, if we substitute over here the stripping section operating line equation would be y m plus 1 is equal to L bar by L bar minus W x m minus W by L bar minus W into x W ok. So, this is the equation of the operating line for the stripping section.

(Refer Slide Time: 09:12)



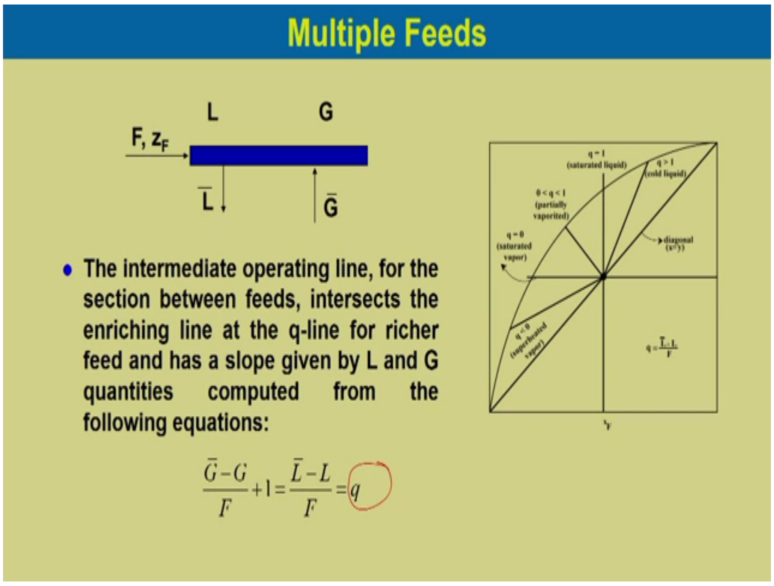
Now, it has a slope of L bar by L bar minus W slope of the operating line section and it passes through the point x W x W which lies on the diagonal.

(Refer Slide Time: 09:25)



Now, you can see for the least number of stages at a given reflux ratio, the feed are introduced at the stage which construction on the diagrams straddle their q-line. So, basically we have two different feed. So, first we have to draw the operating line for the rectifying section considering the starting point and the intercept on the y and then we have based on the feed condition we can draw the feed line equation, feed line. And similarly I know, we can draw the feed line for both the section know both the feed few line we can draw which is shown over here.

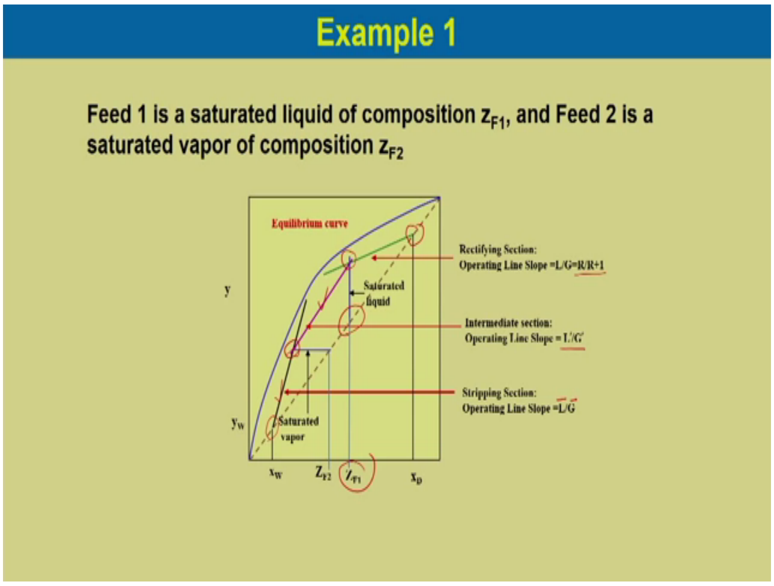
(Refer Slide Time: 10:14)



So, you can see know if we do the balanced equation for feed line. So, this is F z F would be equal to know which is entering into the feed L is the top column know, liquid flow and now from the top of the section and know from the top of the section and know from feed tray it is L bar and going into the feed know feed tray is G bar and going out from the feed tray is G.

So, like we did know before, we can calculate the slope of the operating line for the q-line is q would be equal to L bar minus L by F. So, with these are the know slope for different q values. So, we can calculate for depending on the feed condition, we can calculate their q-line. We can calculate their values of q and the slope of the q-line and we can plot the feed line that is q-line.

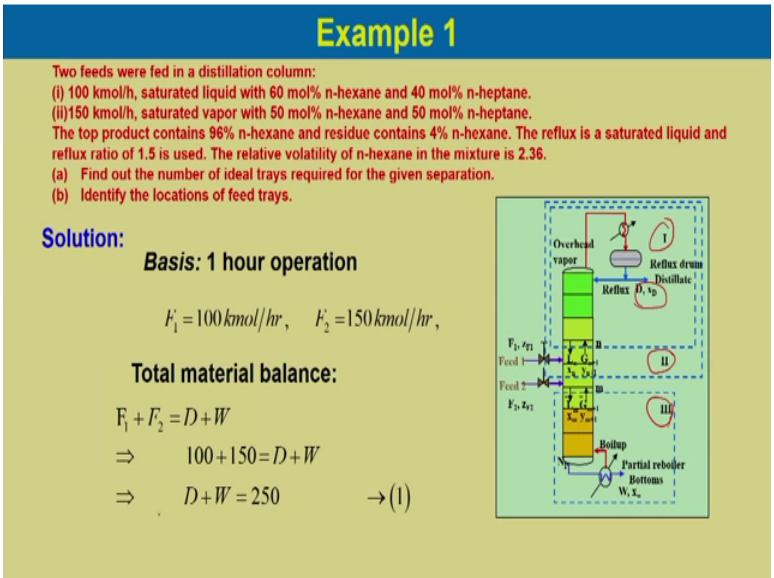
(Refer Slide Time: 11:13)



Now, let us consider feed 1 is a saturated liquid of composition z F1, and feed 2 is a saturated vapor of composition z F2. So, as we have discussing before that know we know the rectifying section operating line, which is balanced equation for the rectifying section above the feed 1 entry. And then we know the stripping section operating line equation its slope and intercept and now we know the feed condition. So, feed 1 is saturated liquid. So, its q-line q values is 1 so, its slope is infinite. So, it will be a vertical line from the feed composition z F1, this is the q-line equation for saturated liquid and this is the feed line equation for the saturated vapor.

As per slope of the operating line in the stripping section we can plot this stripping section operating line and it will intersect the know feed 2 at this location and the stripping section operating line and the feed line with intersects at this location, and this would be satisfied with this operating line between the two feed tray ok. So, which is the line for between the or operating line plot between the two feed tray or it this is the intermediate section operating line slope, which is shown over here L dash by G dash. And for this rectifying section slope is R by R plus 1 and the stripping section operating line is. So, L bar by G bar.

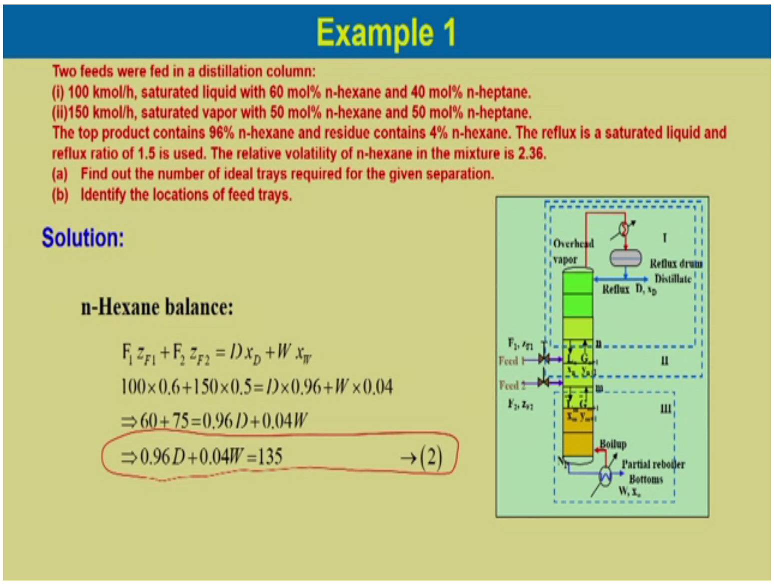
(Refer Slide Time: 13:08)



Now, let us take an example that two feed where feed in a distillation column and having 100 kilomole per hour saturated liquid feed with 60 mole percent n-hexane and 40 mole percent n-heptanes. The second feed is 150 kilomole per hour flow rate and saturated vapor with 50 mole percent n-hexane and 50 mole percent n heptanes. The top product contains 96 percent n-hexane and residue contains 4 percent n-hexane. The reflux is a saturated liquid and the reflux ratio of 1.5 is used, the relative volatility of n-hexane in the mixture is 2.36. We need to find out the number of ideal trays required for the given separation and identify the location of the feed trays.

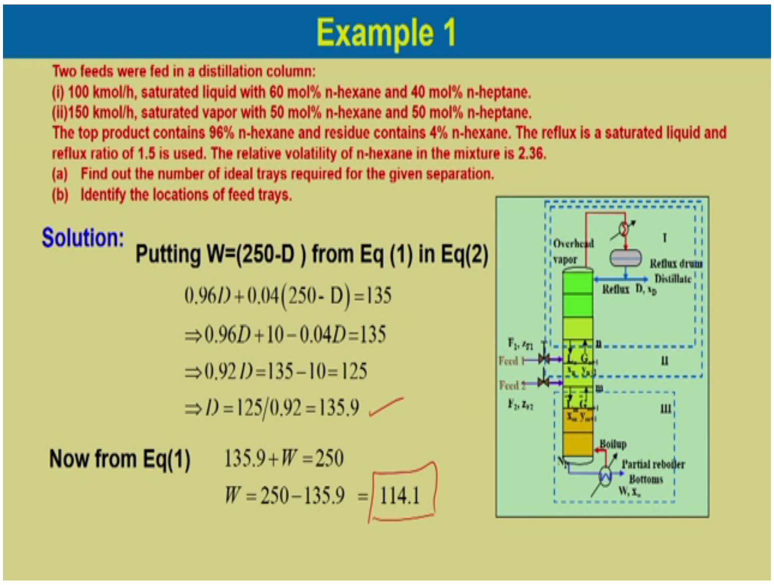
So, like know for the two feed column, we have three different envelope, envelope I envelope II and envelope III and know all the feed condition and their compositions are mentioned over here both bottoms and then the distillate which is coming out. So, basis is 1 hour operation, our feed flow rate F 1 is 100 kilomole per hour and F 2 is 150 kilomole per hour. So, total material balance if we do it would be the feed 1 plus feed 2 would be equal to D plus W. So, F 1 and F 2 is 100 and 150 kilomole per hour would be D plus W. So, D plus would be 250.

(Refer Slide Time: 15:08)



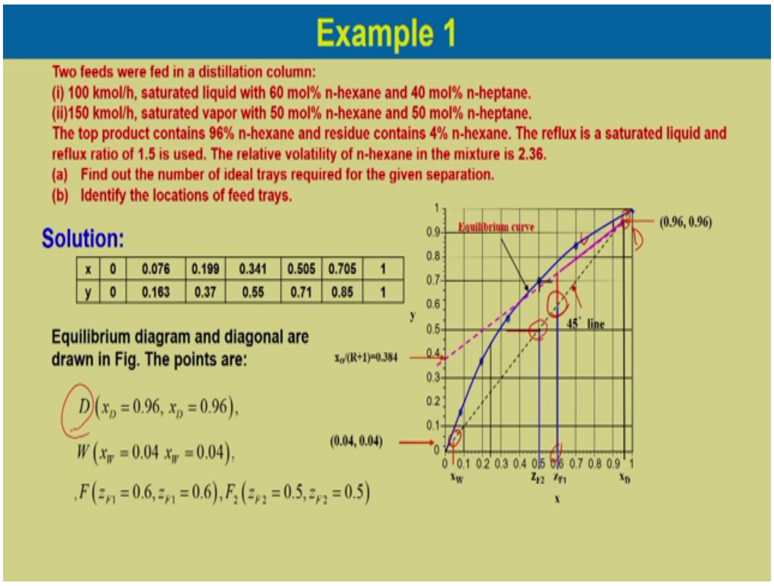
Now, n-hexane balance if we do, so it is F 1 z F1 plus F 2, z F2 would be equal to D x D plus W x W. If we substitute it is 100 into 0.6 because the feed 1 contains 60 mole percent n-hexane and the feed 2 contains 50 mole percent n-hexane. So, 150 into 0.5 and distillate we have 0.96 that is 96 percent n-hexane and 0.04 that is 4 percent n-hexane or normal hexane in the bottoms. So, from here we can get this equation relating D and W that is distillation and bottom. So, we have two equations equation 1 and equation 2 which relates distillate and bottoms and we can calculate D the distillate flow rate and the bottoms flow rate.

(Refer Slide Time: 16:08)



So, from this know putting the values in equation know 2. So, we can obtain so, distillate is 135.9 kilomole per hour and similarly, W would be 114 kilomole per hour. So, we can calculate know by doing the material balance species mole balance and the overall material balance, we can calculate the distillate and bottom flow rate.

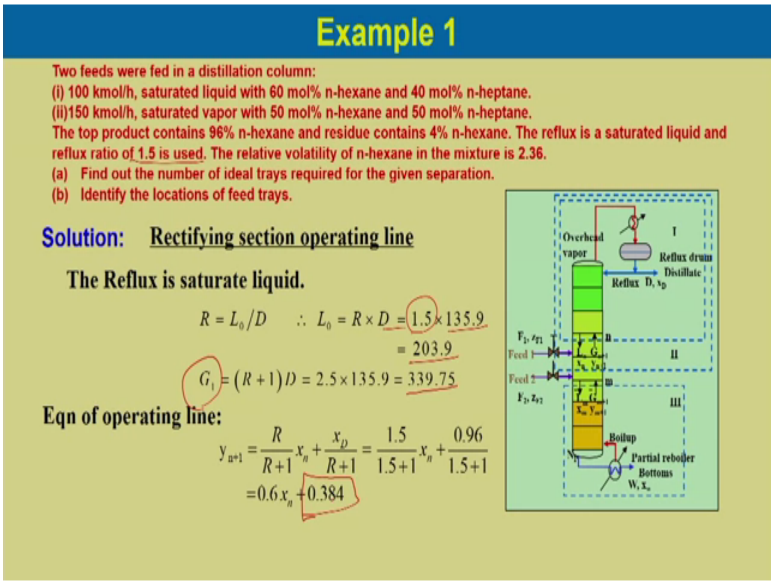
(Refer Slide Time: 16:48)



Now, equilibrium data that relative volatility equation is given. So, equilibrium data we can calculate and we can thought the equilibrium diagram which is shown over here in the blue line.

Now, x D is 0.96 and 0.96 at D location. So, which is over here this is D and this is W that is 0.04 and feed condition is know 0.6 and 0.6 for feed 1. So, which is over here and it is know intercept on the diagonal over here and feed 2 is 50 mole percent. So, it is over here.

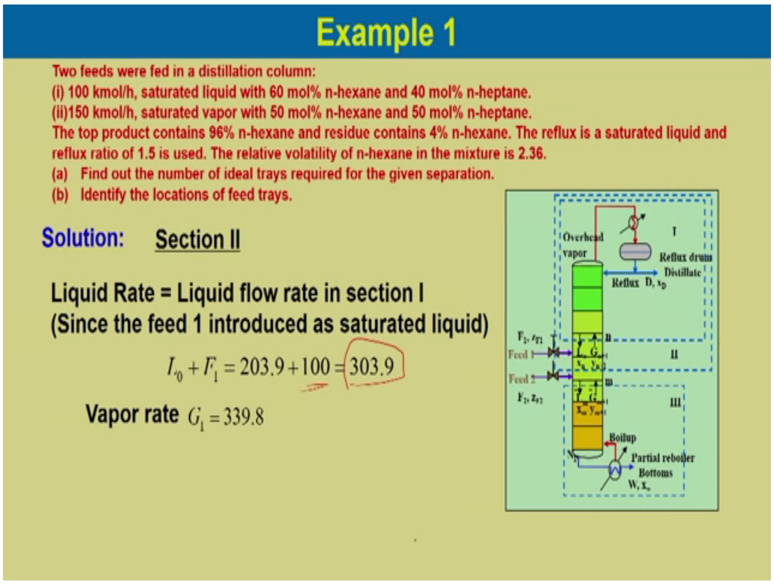
(Refer Slide Time: 17:23)



So, now we can know plot the know we can find out the rectifying section operating line, the reflux is saturated liquid. So, R would be L naught by D. So, which is L naught would be equal to R into D, the reflux ratio is 1.5 which is given over here. So, if we put 1.5 into distillate is 135.9. So, it is L naught would be equal to 203.9. So, the G 1 which is know vapor flows from the top tray is R plus 1 into D which is 2.5 into 135.9 so 339.75.

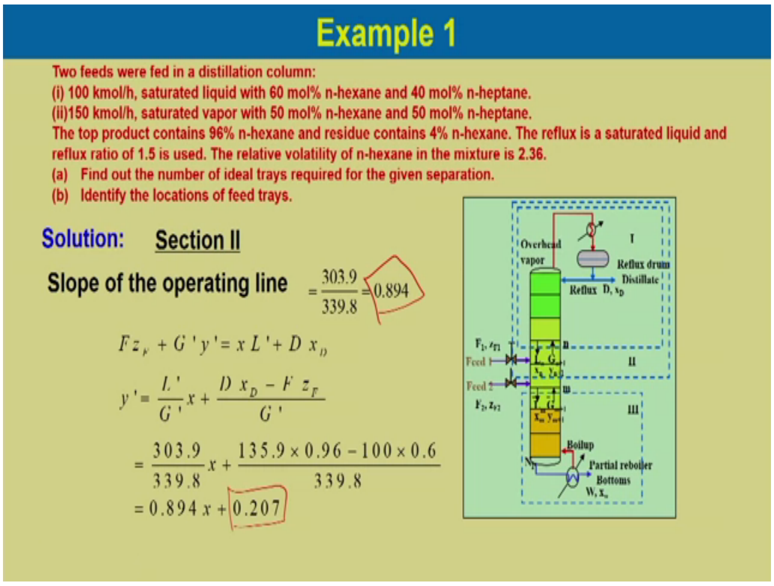
So, G 1 we can calculate and equation of the operating line we can write over here. So, R by R plus 1 into x n plus x D by R plus 1. So, which is equal to this and finally, we will get y n plus 1 would be equal to 0.6 xn plus 0.384. So, this is the intercept of the operating line in the stripping section.

(Refer Slide Time: 18:43)



Now, for the section II liquid rate would be equal to liquid rate in the section I, because since the feed 1 introduced as a saturated liquid. So, L naught plus F 1 would be equal to 203.9 plus 100 that is the feed which is introduced. So, it is 303.9 and vapor flow is 339.8.

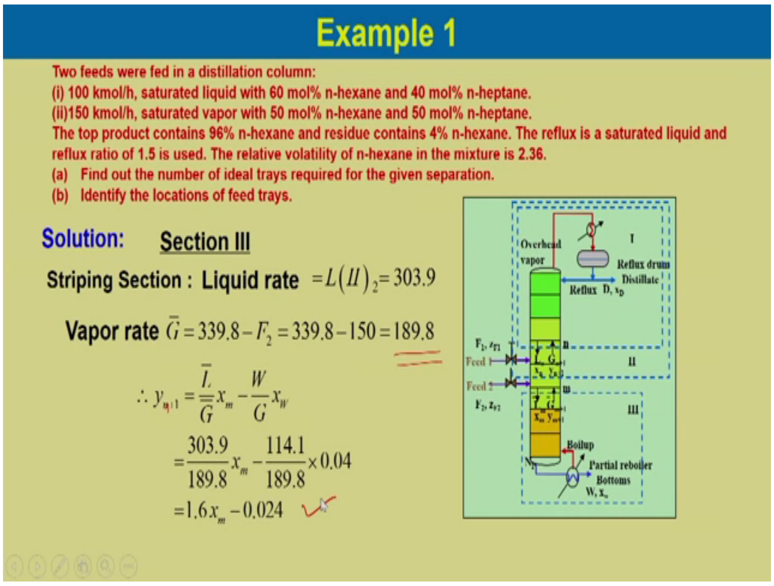
(Refer Slide Time: 19:16)



So, slope of the operating line would be 0.894 in this section II.

Now, if we do for section II the species mole balance Fz F plus G dash y dash would be equal to x L dash plus D x D and if we just substitute the values. So, we would obtain y naught would be equal to 0.894 x plus 0.207. So, this is the know intercept for this know operating line.

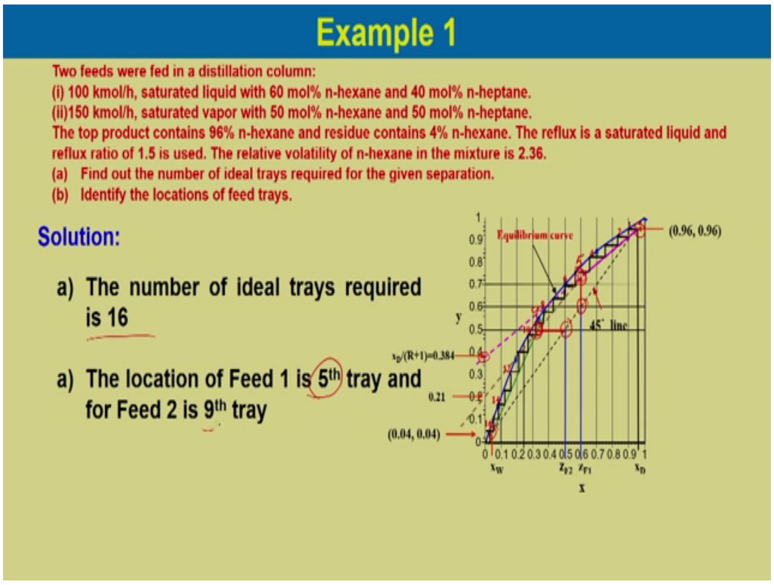
(Refer Slide Time: 19:58)



And for section III, the liquid rate would be L into know section II the liquid rate in the section II. So, which is 303.9 and vapor rate because feed is saturated vapor. So, it would be 339.8 minus F 2. So, it would be 339.8 minus 150. So, which is 189.8.

So, and the total know rectifying section operating line equations would be know y n plus 1, this is y m plus 1 would be equal to 1.6 x m minus 0.024. So, this is the rectifying section operating line equation.

(Refer Slide Time: 21:02)

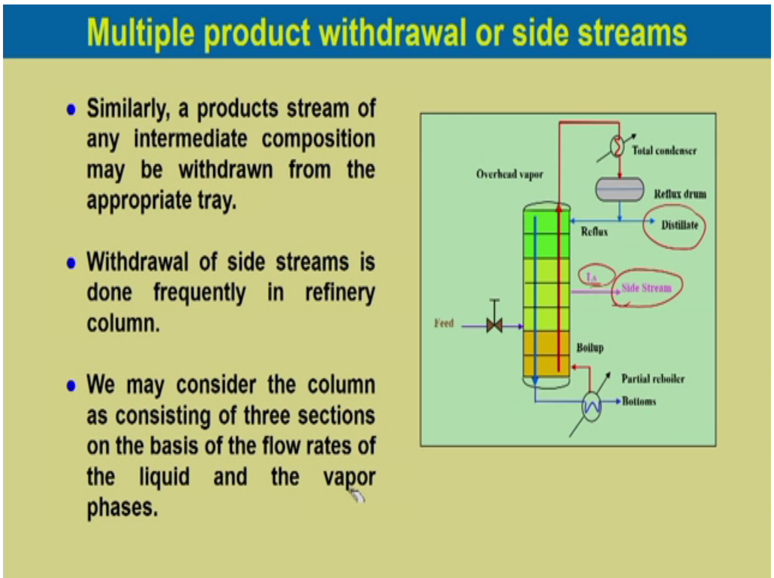


So, now if we just plot for stripping section operating line, you can locate the two feed conditions on the 45 degree diagonal and you can locate the distillate condition here. And from the operating line we have the rectifying section that is the intercept 0.384 x D by R plus 1 we can plot the operating line in the top section, section I. We can draw the feed line depending on the feed condition here is feed 1 is saturated liquid. So, vertical line it two is saturated vapor so horizontal line q-line for this section for feed 2.

We know the intersection point between the feed line of feed 1 and the rectifying section operating line and similarly the with the slope of the stripping section operating line, we can get the intersection point between the feed 2 and the stripping section and operating line. Now we can join these two intersection point for the parting line in the intermediate section. Now, on this operating line starting from x D x D, we can just step of using the McCabe-Thiele method to calculate the ideal trays required for the separation and which is about 16 number of ideal trays required for the separation.

Now, the location of the feed tray 1, you can see over here. So, feed 1 which is intersecting at this location; so, this is tray 4 and this is tray 5. So, location of the feed tray is basically 5th tray, and know location of feed 2 you can see over here the feed condition is over here. So, it is intersecting at this point and the tray is 9th tray. So, the location of the feed tray is 5th tray and location for the feed 2 is 9th tray.

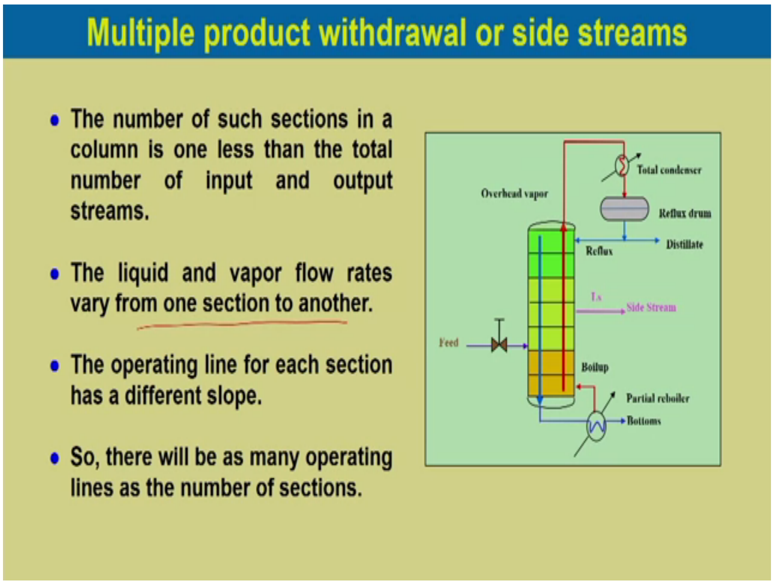
(Refer Slide Time: 23:20)



Now, we will discuss about the multiple product withdrawal or side streams. So, if we have a know instead of one product know distillate out outs. So, we have one more side stream in the product withdrawal. So, in this case how to calculate the number of ideal trays required for the separation. So, you can see over here there is a Ls which is know side stream taken with a single feed in and multiple product out.

So, one is distillate out another is side stream taken. Similarly, a product stream of any intermediate composition maybe withdrawn from the appropriate tray. Withdrawal of side stream is done frequently in refinery column, because you need different stage cut or with different composition for the refinery products. So, that is a usual practice in case of refinery, there is a frequently they used to take different cuts from the distillation column. We may consider the column at consisting of three sections on the basis of flow rates of the liquid and the vapor phases.

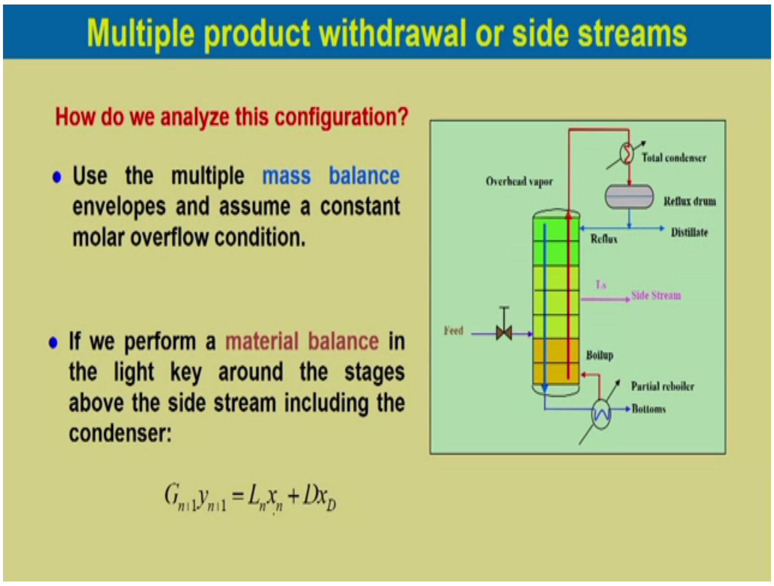
(Refer Slide Time: 24:42)



The number of such sections in a column each one less than the total number of input and output streams. The liquid and vapor flow rates vary from one section to the other section because you have intermediate product withdrawal.

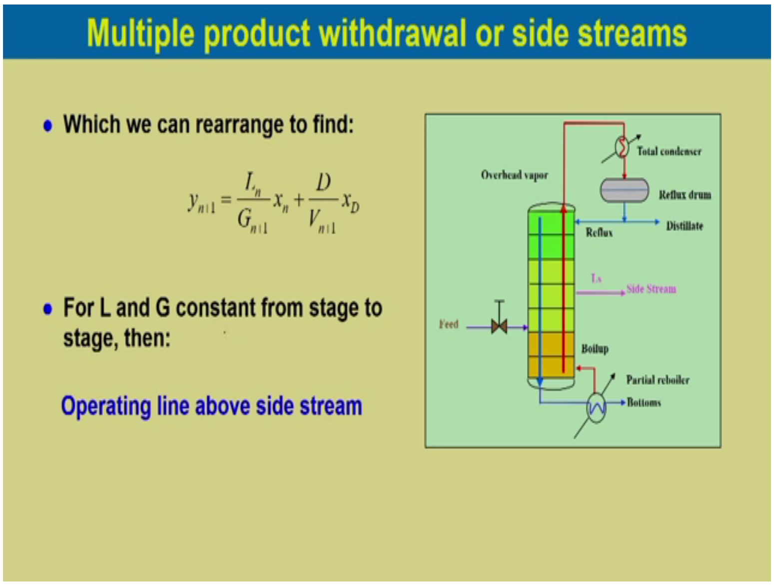
So, operating line for each sections has a different slope. So, there will be as many operating lines as the number of sections are increased depending on the side streams.

(Refer Slide Time: 25:18)



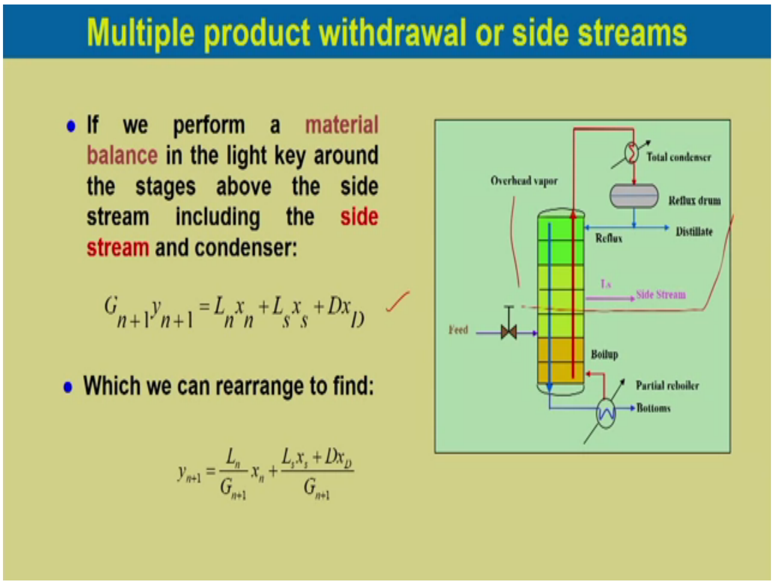
How do we analyze this configuration? Use the multiple mass balance envelops and assume a constant molar overflow condition. If we perform a material balance in light key around the stages above the side stream including the condenser. So, this is side streams and above that if you take the section we can write G n plus 1 into y n plus 1 would be equal to L n x n plus D x D.

(Refer Slide Time: 25:55)



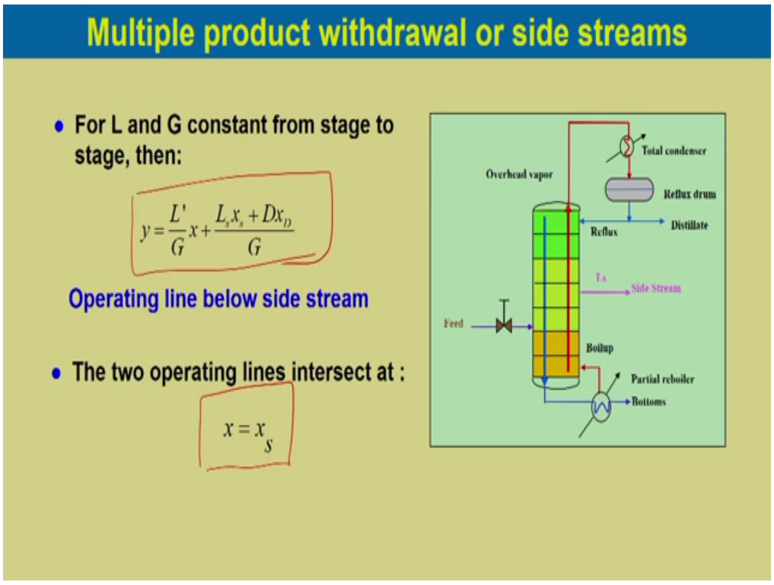
And from here we can write know y n plus 1 would be equal to L n by G n plus 1 into x n plus D by V n plus 1 into x D. For L and G constant from stage to stage, then operating line above the side stream.

(Refer Slide Time: 26:15)



If we perform a material balance in the light key around the stages above the side stream including the side steam and condenser, we can write G n plus 1 into y n plus 1 would be equal to L n x n plus L s x s plus D x D. So, this is including the side stream; so, envelope over here above this.

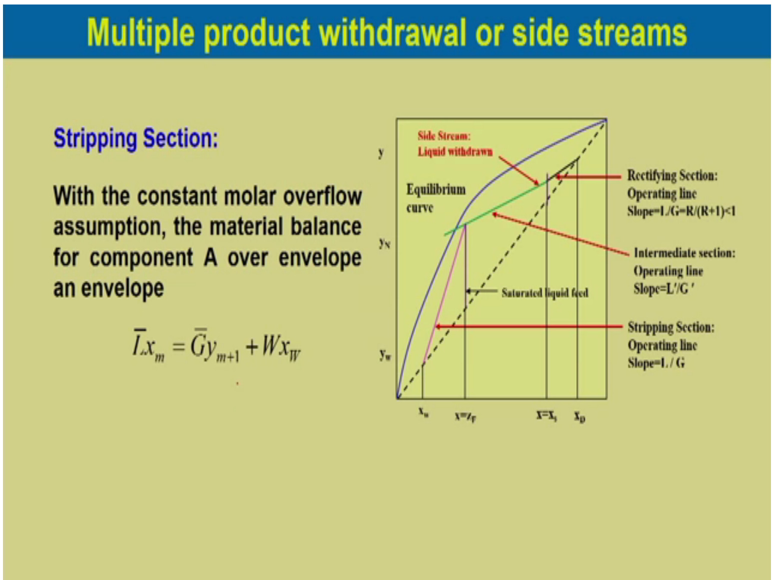
(Refer Slide Time: 27:06)



Now, this we can rearrange and we can write y n plus 1 would be equal to L n by G n plus 1 into x n plus L s x s plus D x D by G n plus 1. For L and G constant from stage to stage then we can write y would be equal to L dash by G into x plus L s into x s plus D into x D y G.

So, operating line below the side stream what will happen the two operating line intersects at x is equal to x s. This is the operating line below the side stream. So, two operating line intersects at x is equal to x s.

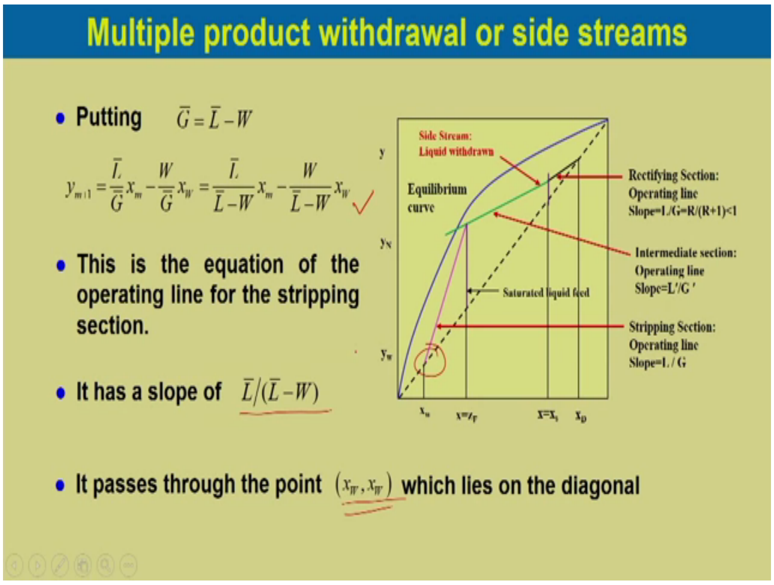
(Refer Slide Time: 27:53)



Now, if you consider stripping section with constant molar overflow assumption the material balance for component A over envelope know over an envelope we can write L bar into x m would be equal to G bar y m plus 1 plus W x W.

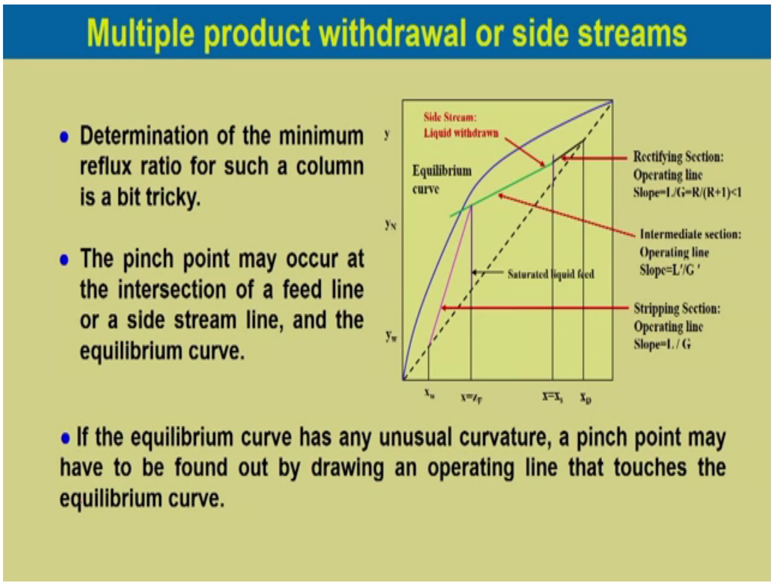
So, putting G bar would be equal to L bar minus w from the overall material balance in the stripping section, we can write y m plus 1 would be equal to L bar by L bar minus W x m into x m minus W by L bar minus W into x W.

(Refer Slide Time: 28:14)



So, this is the stripping section operating line equation and it has slope L bar by L bar minus W as usual, it passes through the point x W, x W and it lies on the diagonal.

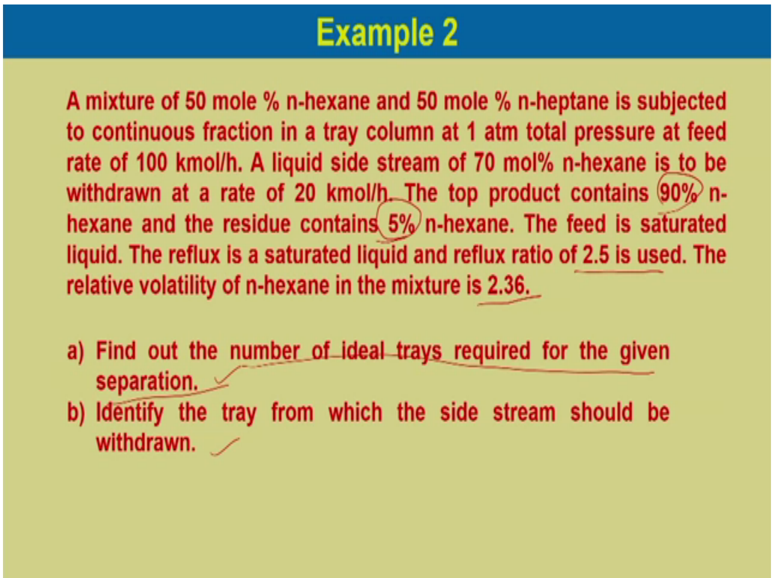
(Refer Slide Time: 28:52)



So, determination of the minimum reflux ratio for such a column is a bit tricky in this case, the pinch point may occur at the intersections of a feed or a side stream line and the equilibrium curve.

So, if the equilibrium curve has any unusual curvature, a pinch point may have to be found out by drawing an operating line that touches the equilibrium curve. That is the tangent operating line to the equilibrium curve which we have done for the inflection points in the equilibrium curve as earlier.

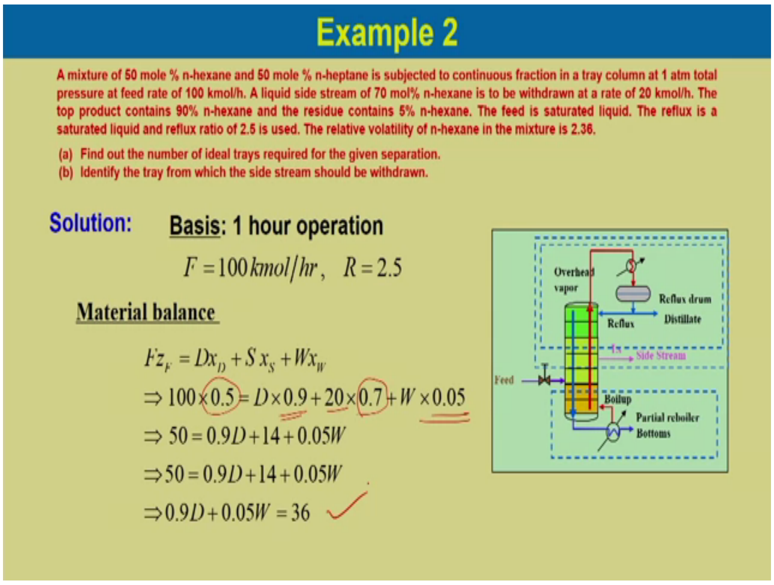
(Refer Slide Time: 29:34)



Now, let us take know an example. A mixture of 50 mol percent n-hexane and 50 mol percent n-heptane is subjected to continuous fractionation in a tray column at one atmosphere pressure at feed rate of 100 kilo mol per hour. A liquid side stream of 70 mol percent n-hexane is to be withdrawn at a rate of 20 kilo mol per hour. The top product contains 90 percent n-hexane and the residue contents 5 percent n-hexane. The feed is saturated liquid the reflex is a saturated liquid and reflux ratio of 2.5 is used the relative volatility of n-hexane in the mixture is 2.36. Please note that although we will do the calculation as for example, based on point know 5 mol percent in the residue, but as per the mass balance it has to be know if the product is 90 percent n-hexane it has to be 10 percent n hexane.

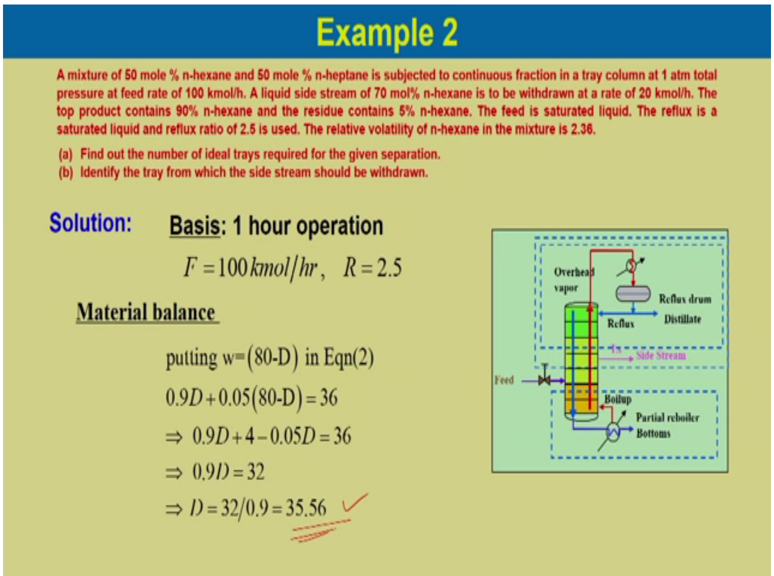
But for the procedure to find out the number of ideal trays required for a given separation, the calculation procedure would be same. So, there will not be any difference and also identify the tray from which is the side stream should be withdrawn. So, to do that the procedure remains same, but calculations will little bit change based on the actual mass balance.

(Refer Slide Time: 31:02)



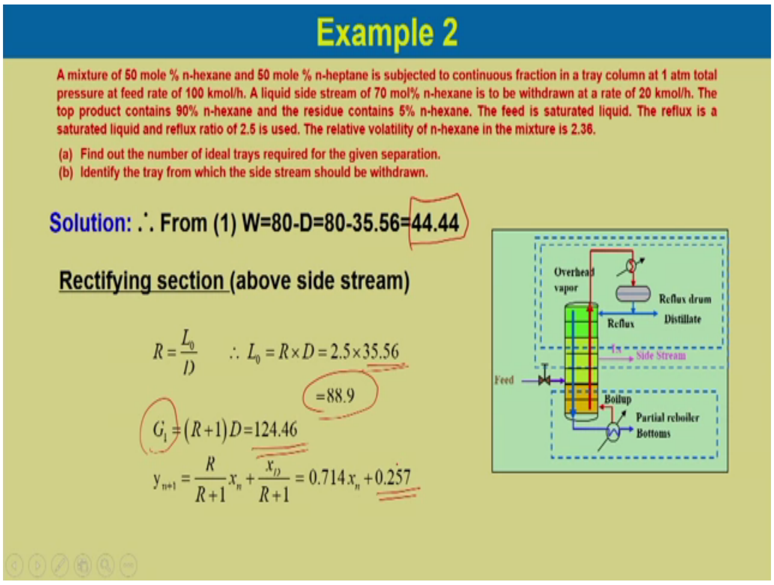
So, basis is 1 hour operation and we have feed flow rate of 100 kilo mol per hour the reflux ratio is 2.5. Now if you do the species mol balance. So, it would be F z F would be equal to D x D plus S x S plus W x W. The feed contains 50 mol percent n-hexane; so, it is 0.5 into 100 into 0.5 and know D into 0.9 that is distillate and we have know 20 kilo mol per hour withdrawal rate for the side stream having know 70 mol percent of n hexane. So, it is 0.7 and your bottoms contains know W is 0.05. So, if you do the balance equations. So, it would be 0.9 D plus 0.05 W would be equal to 36. So, this is material balance equation relating distillate and bottom product.

(Refer Slide Time: 32:17)



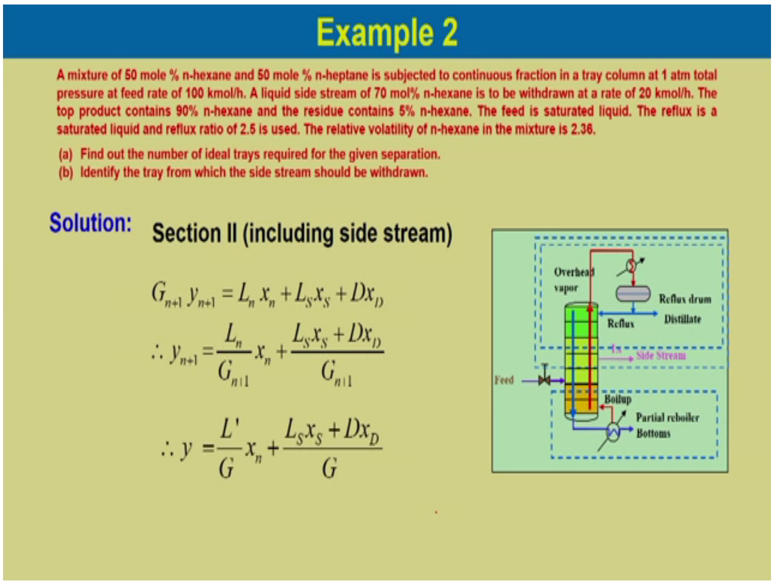
And though putting the total material balance over here. So, we can get distillate is about know 35.56 kilo mol per hour. So, this is distillate. And similarly know we can calculate the bottom product which is 80 minus D which is equal to know 80 minus 35.36 which is 44.44.

(Refer Slide Time: 32:33)



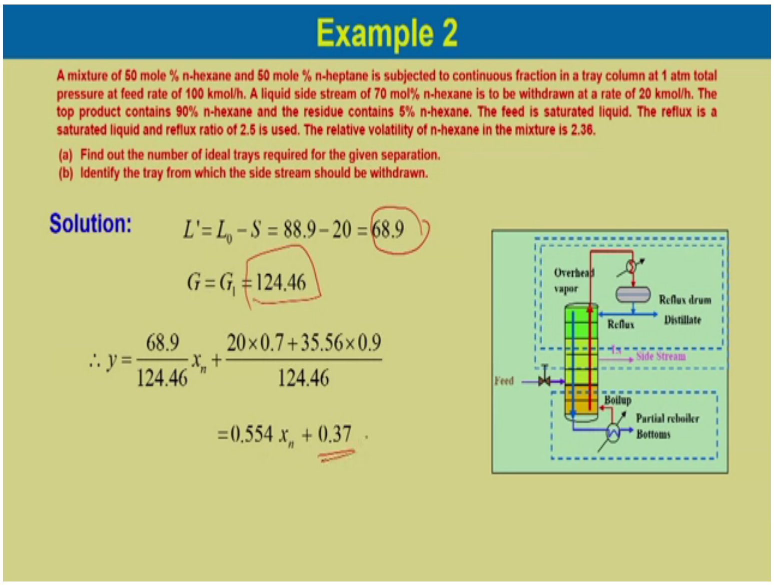
So, W is known to us and distillate is also known to us. So, rectifying section above the side stream we can obtain the operating line equations, reflux ratio is L naught by (( )); so, L naught would be R into D which is 2.5 into 35.56 distillate. So, which is L naught is 88.9 kilo mol per hour. G 1 we can calculate which is know R plus 1 into D which is 124.46 that is the vapor flow at the top of the tray from the top tray. So, the equation of the operating line is y n plus 1 would be equal to R by R plus 1 into x n plus x D by R plus 1. So, it would be know 0.714 x n plus 0.257 is a intercept.

(Refer Slide Time: 33:50)



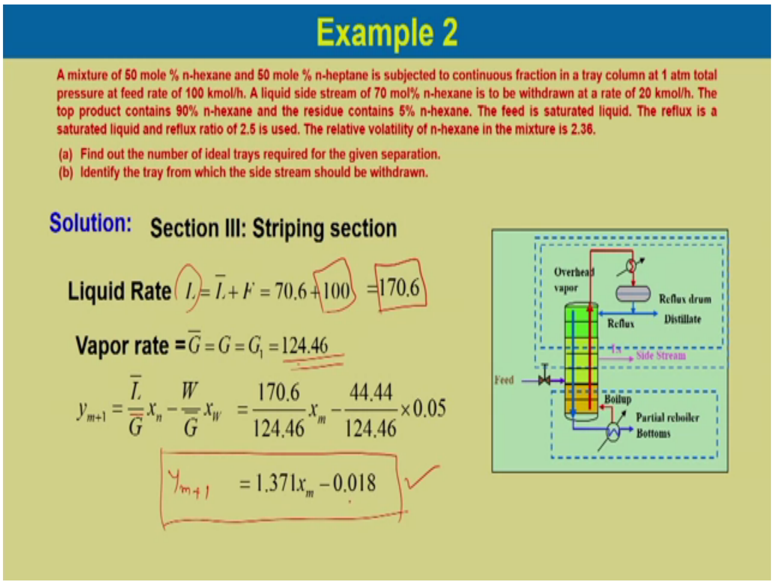
Now, section II including the side streams the material balance equation would be y n plus 1 would be equal to L n by G n plus 1 into x n plus L s x s plus D into x D by G n plus 1.

(Refer Slide Time: 34:09)



If we substitute the values L dash would be equal to L naught minus S. So, which is 68.9 kilomol per hour G would be equal to G 1. So, it is 124.46. So, operating line equation y would be equal to 0.554 x n plus 0.37.

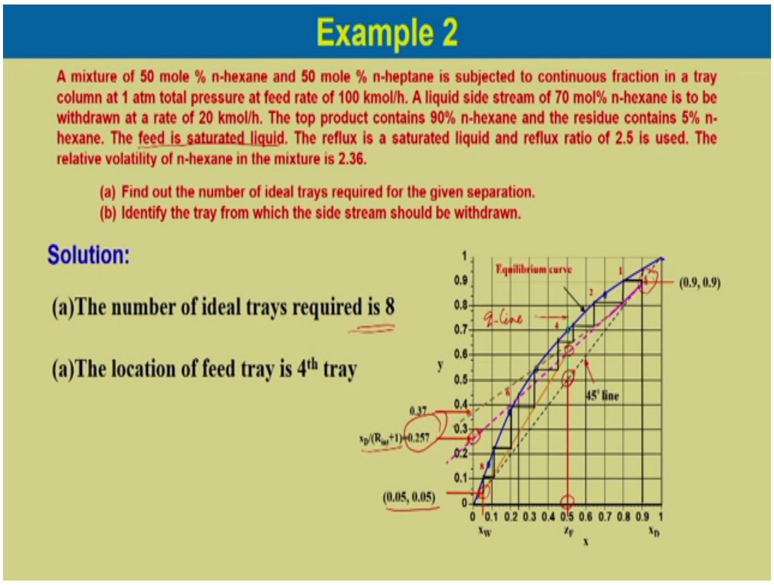
(Refer Slide Time: 34:33)



Now, for section III which is know stripping section the liquid rate L is equal to L bar plus F. So, L bar is know 70.6 plus know feed is 100 kilo mol per hour. So, it would be 170.6 that is kilomol per hour is the liquid rate. The gas vapor rate remains know constant for this section as well it is G bar would be equal to G would be equal to G 1 which is 124.46.

Now, the operating line equation for the stripping section is y m plus 1 would be equal to L bar by G into x n minus W by G bar into know x W. So, this is you know equal to know 170.6 divided by 124.46 into x m minus 44.44 divided by 124.46 into 0.05. So, you will have now y m plus 1 would be equal to 1.371 x m minus 0.018. So, this is the know equation for the operating line in the stripping section.

(Refer Slide Time: 36:09)



So, we know the composition over here in the rectifying section is 0.9, 0.9 x (( )), x D and we know over here 0.05, 0.05 in the stripping section.

So, two extreme points or two end points and then feed is saturated liquid and feed condition is 50 mol percent n hexane. So, this is the 0.5 so, on 45 degree diagonal this is the point feed condition and we can draw the q-line. So, this is the q-line or the saturated liquid feed. And we can also calculate the x D by R internal plus 1 or x D by R plus 1 which is 0.257 with this intercept and the distillate condition over here we can plot the operating line, which will intersect the feed line at this location. And we know the stripping section operating line condition.

So, we draw the operating line in the rectifying section over here. So, this is how we calculated the stripping section operating line and we connect over here. So, the number of ideal tray required is in this case, know we can calculate is, if you see over here by staircase construction it would be 8 number of ideal trays required. So, this is the location of the fourth tray.

So, thank you very much for attending this lecture and we will continue our discussion on the distillation for the next couple of lectures.