Mass Transfer Operations – I
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Distillation
Lecture -35
Multistage batch distillation with reflux

Welcome to 10th lecture of module 5 of Mass Transfer Operation. In this module, we are discussing Distillation operation. So, before going to this lecture, let us have a recap on our previous lecture. In our previous lecture we have discussed mainly 2 things; one is multiple feed.

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So, far multiple feeds we have seen how to obtain the different operating lines for different sections and how to calculate the number of ideal stages requires using the operating line and the equilibrium line. The second thing we have considered in this case is the multiple product withdrawal. This is also like in case of multiple feeds we have the number of stages required and then feed plate locations we have determined.

But in case of multiple product withdrawal we have also seen how to calculate the number of ideal trees from where product is withdrawn. Now in this lecture we will now mainly discuss one important thing which is know multistage batch distillation with reflux.

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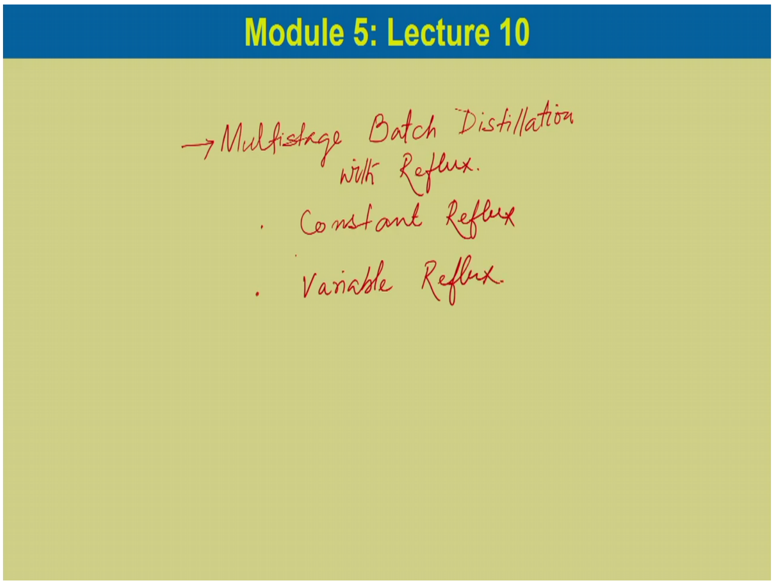

So, earlier we have discussed know multi know batch distillation without reflux, in this case now we will discuss badge distillation with reflux. Under which we have 2 different condition; one is constant reflux and second thing we will considered variable reflux.

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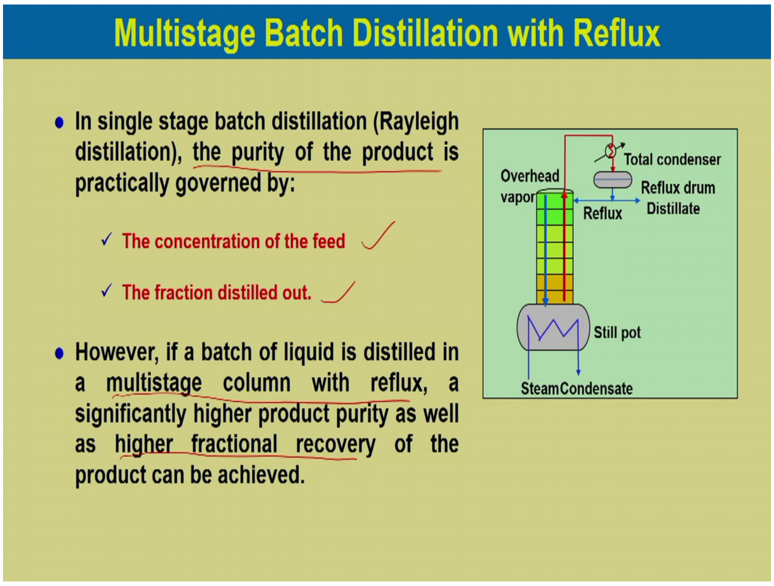

So, multistage batch distillation with reflux. So, you can see in earlier case we did not had any reflux into the batch distillation column. So, we had a steel pot and you have a different stages in the column and then there is a condenser and then reflux drum and you have a reflux ratio you can control and you can get the product outlet at the top as a distillate. So, in single stage batch distillation that is Rayleigh distillation which we have discussed before, the purity of the product is practically governed by the concentration of the feed and second thing is the fractions distilled out.

So, these two parameters the concentration of the feed and the fraction distilled out this will determine the purity of the product you are getting in a single stage distillation unit we call it know Rayleigh distillation. However, if a batch liquid is distilled in a multistage column with reflux a significantly higher productivity as well as higher fractional recovery of the product can be achieved. If we use the multistage in state of single stage and also control the reflux or if we give the reflux back to the batch distillation column, we could achieve higher purity of the product and also the fractional recovery of the product of the solute will be increased.

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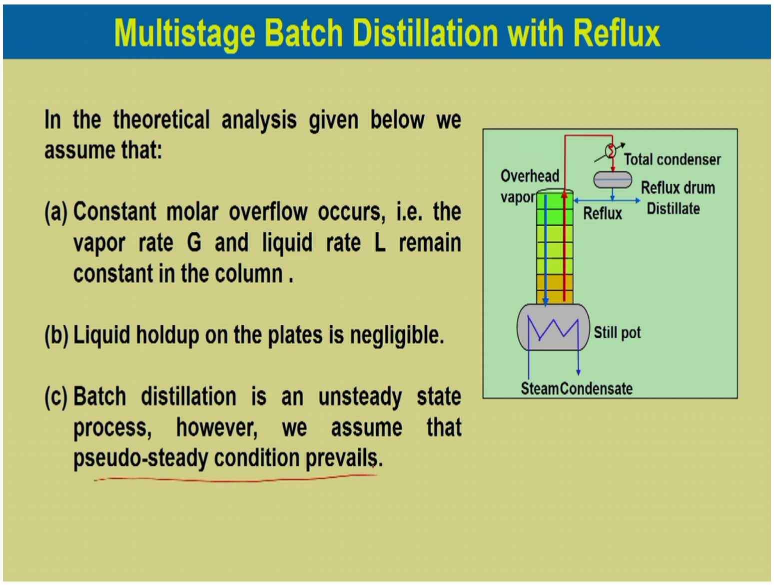

In the theoretical analysis given below we assume certain things one is constant molar overflow occurs, that is the vapor rate G and the liquid rate L remains constant in the column. So, that is the first assumptions we will do for the theoretical analysis of multistage batch distillation with reflux. Liquid holdup on the plates is very negligible and third thing we will assume batch distillation is an unsteady state process, but in this case we assume that the pseudo steady state condition prevails.

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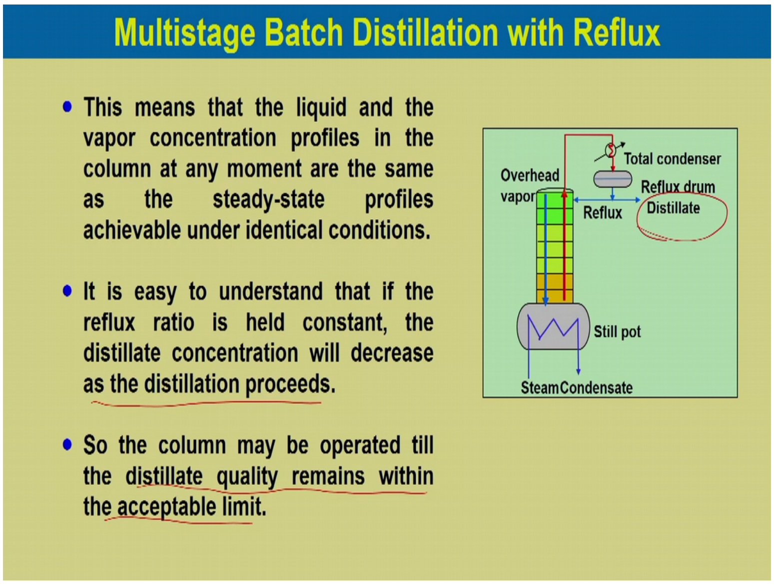

That means, the liquid and the vapor concentration profile in the column at any moment are the same as that the steady state profiles achievable under identical conditions. So, we call it pseudosteady state condition, which prevails in case of batch distillation with reflux for a multistage batch distillation column.

It is easy to understand that if the reflux ratio is held constant the distilled concentration will decrease as the distillation proceeds. Because as you know initially in a batch distillation column when the you know steel the steel pot is heated of the solution or the mixture, the more volatile component will be reach much richer in the distillate. So, the initially the product concentration will be much higher of the more volatile component at the top. As long as the distillation will proceeds the composition will gradually change and more of the less volatile components will also makes because the steel pot contains less quantities of the more volatile components.

So, as long as the distillation will proceed the composition of the solute concentration will decrease. So, the column may be operated till the distillate quality remains within the acceptable limits. Depending on our requirements of the average composition of the distillate the product composition, we need for the solute or more volatile components. Until unless it is within the acceptable limit we can continue our distillation and we stop where the quality desired quality is required.

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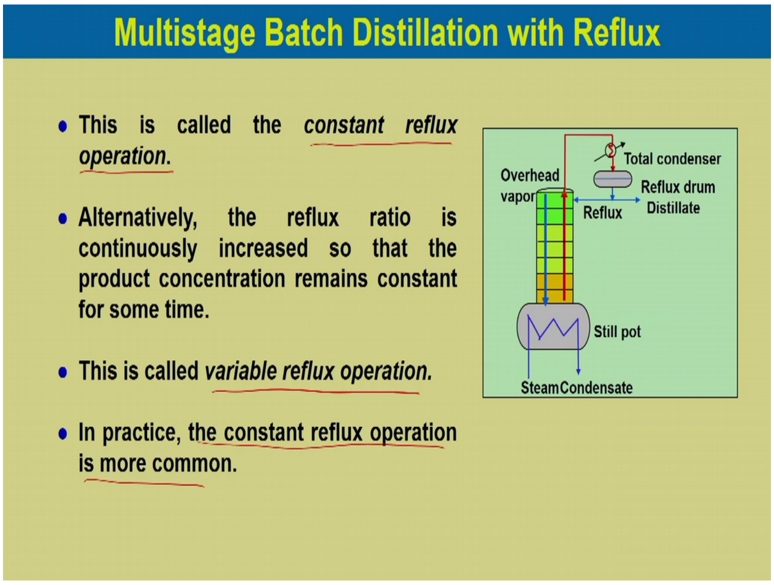

So, until that period we can operate the distillation for a fixed reflux ratio or constant reflux ratio, this is called the constant reflux operation. Alternatively what we can do the reflux ratio is continuously increased so, that the product concentration remain constant for sometime. So, what we can do? If we want to have a high purity product at the distillate, we can change the reflux ratio from very low to very high. So, reflux ratio will be changed in such a way that the product concentration does not change for a certain period of time.

This is called variable reflux operation. So, in practiced constant reflux operation is the more common. So, constant reflux ratio operation is very easier to know operator and that is most common in case of multistage batch distillation with reflux.

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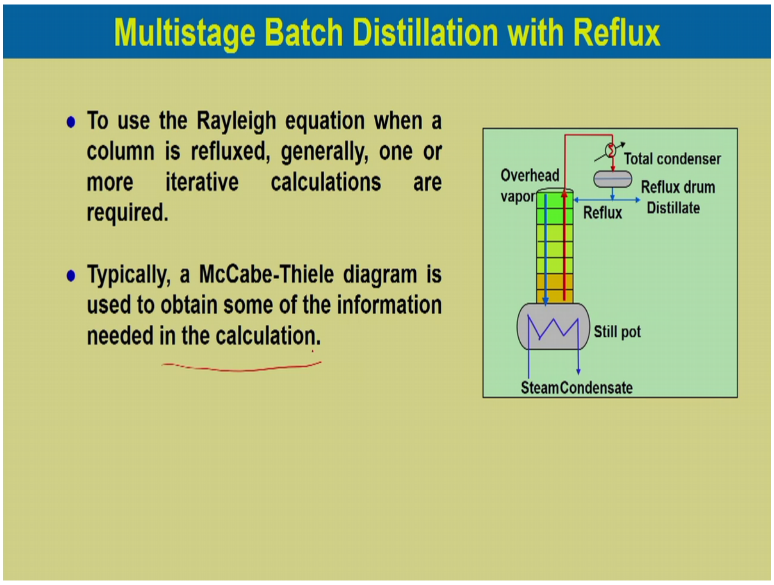

To use the Rayleigh equation when a column is refluxed, generally one or more iterative calculations are required. So, to calculate the you know minimum number of trees required for a you know particular separation if we want to use the Rayleigh equation, then we have few iterations which would be required for the multistage batch distillation with reflux. Typically a McCabe-Thiele diagram is used to obtain some of the information needed in the calculation.

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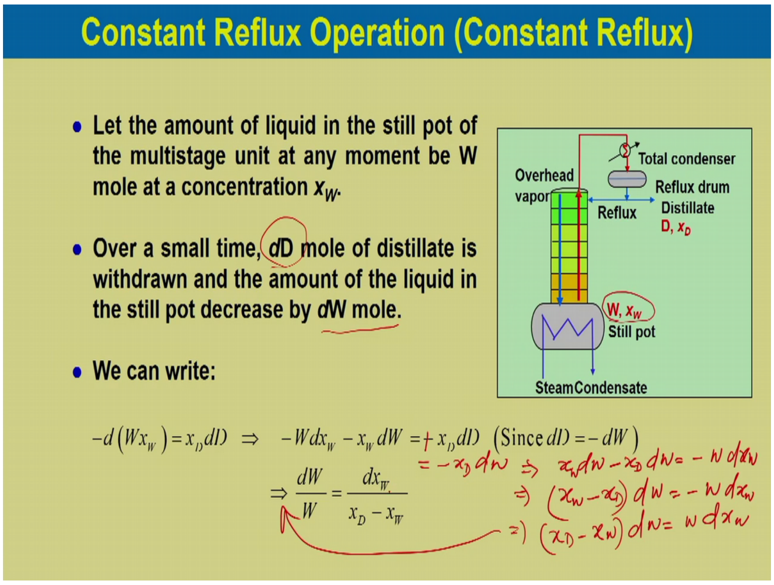

Now, let us consider the first case constant reflux operation that is constant reflux. So, reflux ratio remains constant, so the product concentration will gradually change. And let the amount of the liquid in the steel pot of the multistage unit at any moment be W mole and at concentration x W. So, this is the total number of mole at anytime t, W is the mole in the steel pot and know x W is its mole fraction the a mole volatile component x W. Over a small time dD mole of distillate is withdrawn and the amount of the liquid in the steel pot decreases by dW mole.

So, the amount of distillate we withdraw at this location same amount of you know liquid which will decrease in the steel pot in a very small time dD. So, we can write from here minus d W xW would be equal to xD dD which would be equal to minus W d x W minus x W d W would be equal to x D dD which is equal to you know minus xD dW because dD is equal to minus dW. So, if we simplify this, from here we can write xW into dW minus xD dW would be equal to minus W dxW. So, from here we can write xW minus xD into dW would be equal to minus W d x W and we can write xD minus xW dW would be equal to W d x W. And from here we can just rearrange we can get dW by W would be equal to d x W by x D minus x W.

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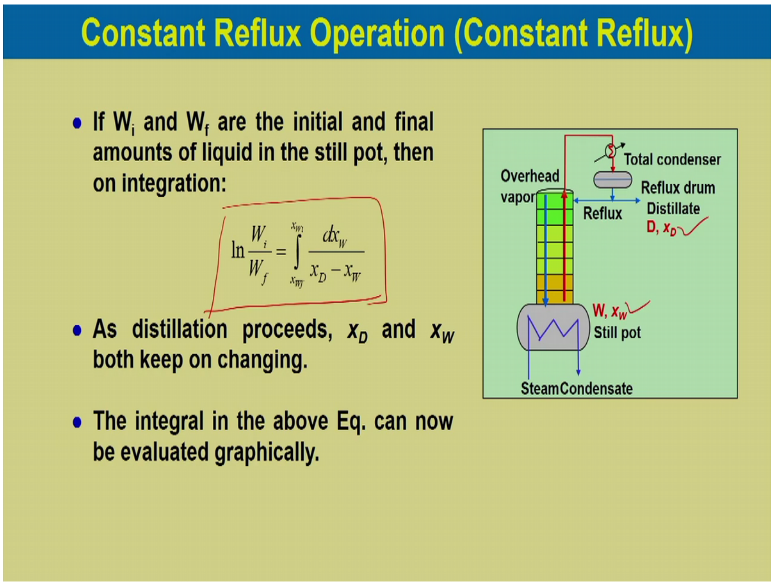

So, now W i and W f are the initial and final amounts of the liquid in the steel pot, then on integration we can get l n W i by W f would be equal to integral x Wf xWi to dxW by xD minus xW. So, this is the integral form of the equation where the composition changes from xWi to xWf as the distillation proceeds xD and xW both keep on changing. So, both on the distillate xD and at the steel pot xW both are keep changing in the batch distillation as the distillation proceeds. So, the integral in the above equation in this equation can be you know evaluated graphically.

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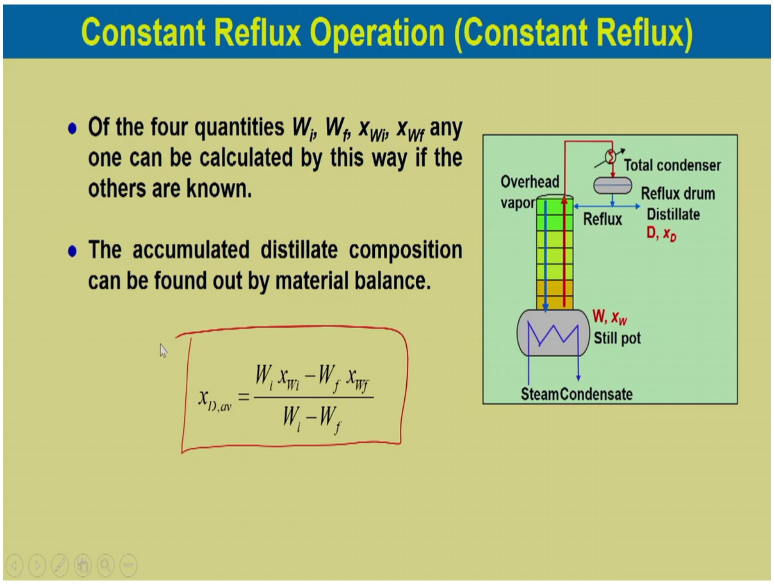

So, of the four quantities that is W i Wf xWi and x W f anyone can be calculated by this way if the others are known. So, the accumulated distillate composition can be found out by the material balance. So, let us do the material balance equation that is xD average would be equal to W i xWi minus W f xWf divided by Wi minus Wf. So, this is based on the material balance equation.

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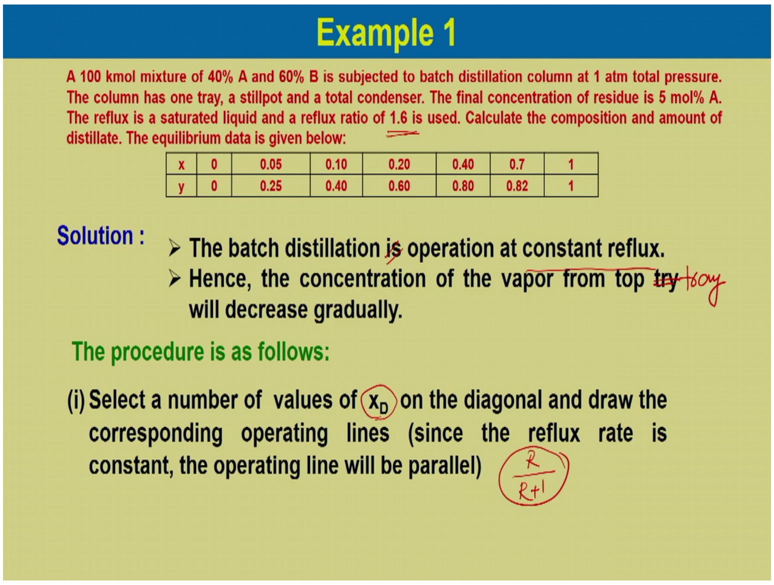

Now let us take an example to understand how we can know calculate the composition and amount of distillate in a multistage batch distillation process with constant reflux. So, for constant reflux you know this problem we will discuss and try to understand how we can calculate the know composition and the amount of distillate. So, a total 100 kilo mole mixture of 40 mole percent A and 50 mole percent B is subjected to batch distillation column at 1 atmosphere pressure, the column has one tray a steel pot and a total condenser.

The final concentration of the residue is 5 mole percent A, the reflux is a saturated liquid and the reflux ratio of 1.6 is used in this case calculate the composition and amount of distillate the equilibrium data is given. So, x and y data given, so, we can plot the equilibrium card.

So, the batch distillation with constant reflux; hence the concentration of the vapor from top tray will decrease gradually and the procedure to be followed select a number of values of xD that is the you know distillate product on the diagonal and draw the corresponding operating lines. Since the reflux rate is constant the operating line will be parallel because R is constant. So, the slope of the operating line R by R plus 1 this slope remains constant.

Since the reflux ratio is given 1.6. So, the procedure is to select any point on the 45 degree diagonal and drawn at different points on the 45 degree diagonal that is xD and then we can plot the parallel operating line because the slope are same.

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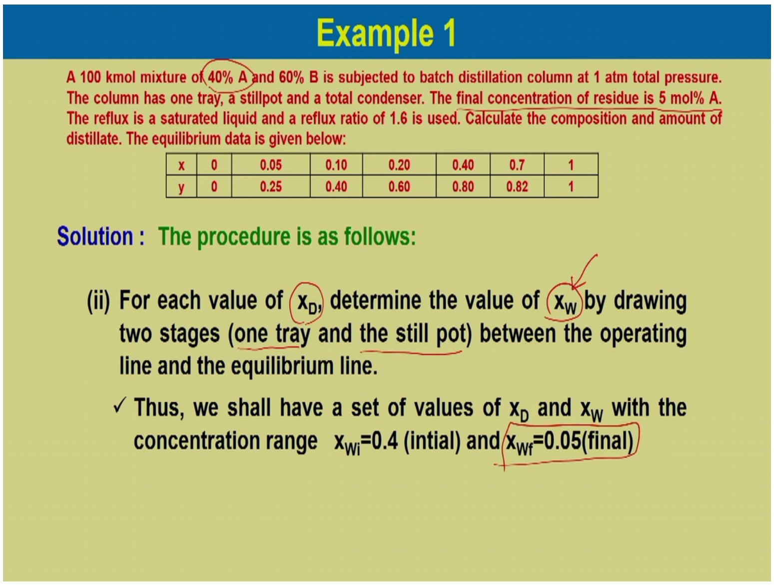

For each values of xD determine the value of x W by drawing two stages one tray and the steel pot between the operating line and equilibrium curve. So, we have one tray and one steel pot from the operating line to the equilibrium curve, if we plot two stages then we can get the values in the steel pot which is x w. So, for a particular values of xD we can calculate xW. Thus we shall have a set of values of xD and xW with the concentration range of x W i that is 0.4 initial concentration which is 40 mole percent A and the final concentration of the residue is 5 mole percent it is 0.05. So, this is the final xf x W f.

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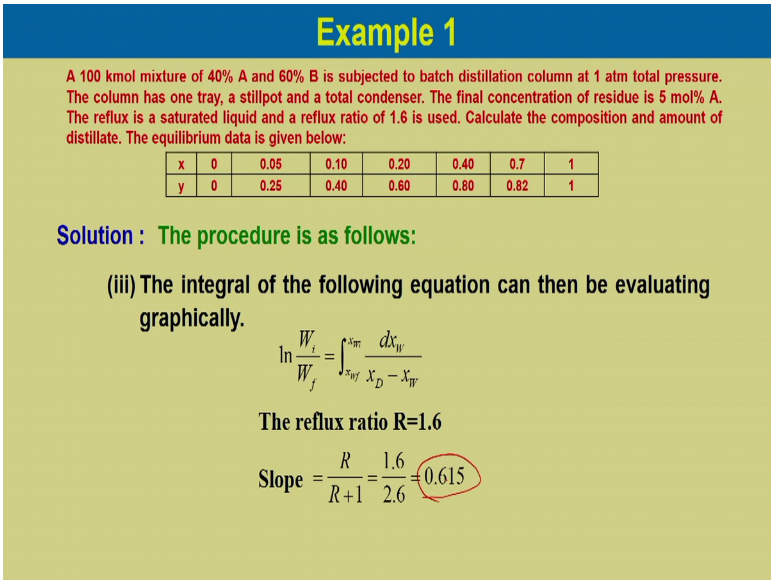

So, the integral of the following equation can be evaluated graphically. So, this is the equation. So, we have set of values of x D x W and from there we can calculate 1 by xD minus xW and we can calculate the area under the curve graphically to get the integral values of these. So, the reflux ratio R is 1.6 which is given. So, slope of the operating line R by R plus 1 would be 1.6 divided by 2.6. So, 0.615 is the slope of the operating line.

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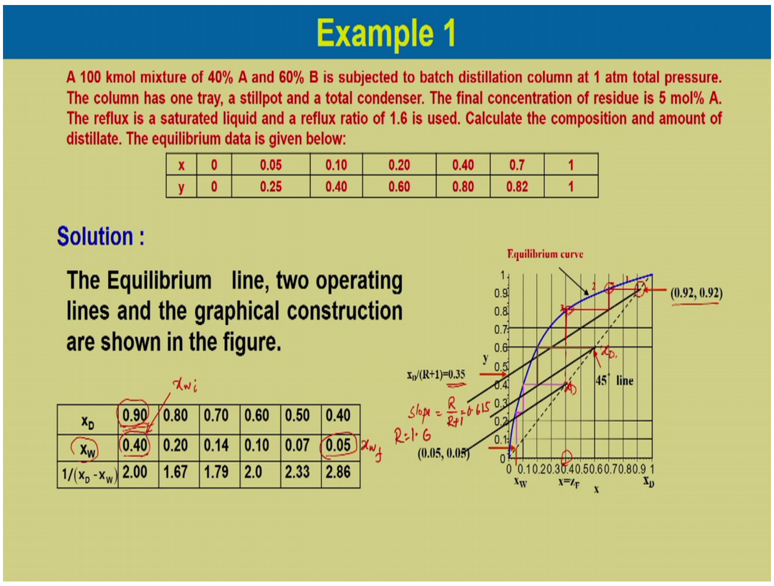

You can see over here. So, this is the equilibrium curve which is given over here and you select any point it is taken from 0.92 9 2, but actually if you just plot the equilibrium line and then two operating lines, both the stripping section and rectifying section you need not to draw the operating line for both the sections.

So, from here with the slope you plot operating lines. So, once one operating line is known. So, other operating line you can draw from the 45 degree diagonal by drawing the parallel lines. We have to come to the initial concentration that is xW. So, we will choose the xD in such a way that we can obtain xW, which is 0.4 at the initial concentration in the steel pot. So, when xD is 0.9 if you plot two trays, you will get the concentration of xW is 0.4.

So, basically you start from a point here and then go to the equilibrium line and then from here you go to the operating line go vertically to the operating line and then go horizontally to the equilibrium curve and corresponding to that you will get the values of you know go to the x axis which is you know around 0.35 with respect to 0.92 if you take you know point at 0.92 and with the slope of the operating line 0.615. So, slope is equal to R by R plus 1 which is 0.615 because R is equal to 1.6 and if it is 0.92 it intersect at 0.35 xD by R plus 1 when the xD is changes and reflux ratio is constant. So, you will have a different curve and we will obtain the values of know for 2 columns we will obtain the values.

So, the similar procedure which is shown over here for you know 0.92 9 2 and for other you know xD values different xD values. So, xW obtained xW from 0.4 to 0.05. So, this is the xWf and this is xWi and corresponding xD you can you know you have corresponding xD is 0.9 and 0.4.

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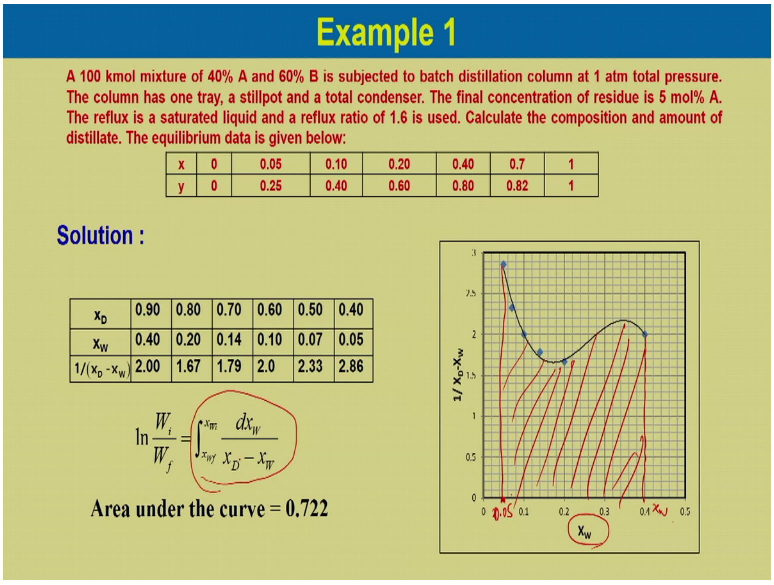

xD and xW known to us. So, we can calculate 1 by xD minus xW from these data, we can plot 1 by xD minus xW versus xW as shown over here. This is starting from 0.4 that is xW up to 0.05. So, which is over here. So, middle of this. So, xW is it is 0.05. So, the area under the curve you can calculate use different methods to calculate the area under the curve either trapezoidal method or Simpson one third rule or some other method to calculate the area under the curve.

So, the area under the curve would be around 0.722 if you calculate. So, it is close to that and this is the equation l n W i by W f is equal to this. So, this is we have calculated which is area under the curve.

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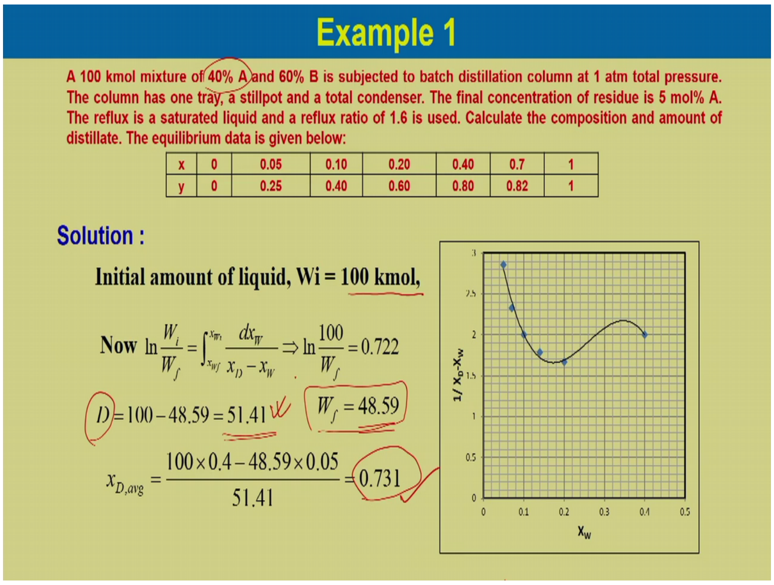

Now, the initial amount of the liquid which is you know W i is 100 kilo mole. So, if you use in this equation. So, ln 100 by W f would be equal to 0.722. So, from here we can calculate W f would be equal to 48.59. So, final moles which is on the steel pot we can obtain these. So, the distillate which we got can be obtained from the total material balance equation which is 100 minus W f which is 48.59.

So, it is 51.41 and then the average composition we can calculate xD average would be equal to 100 into 0.4 40 percent at the feed initially, minus 48.49 the final residue which is 48.59 mole into 0.05 mole fractions divided by distillate that is 51.41. So, it is 0.731, so, xD average is 0.731. So, this is how we can calculate the composition and the amount of distillate. So, this is the composition and this is the amount of distillate.

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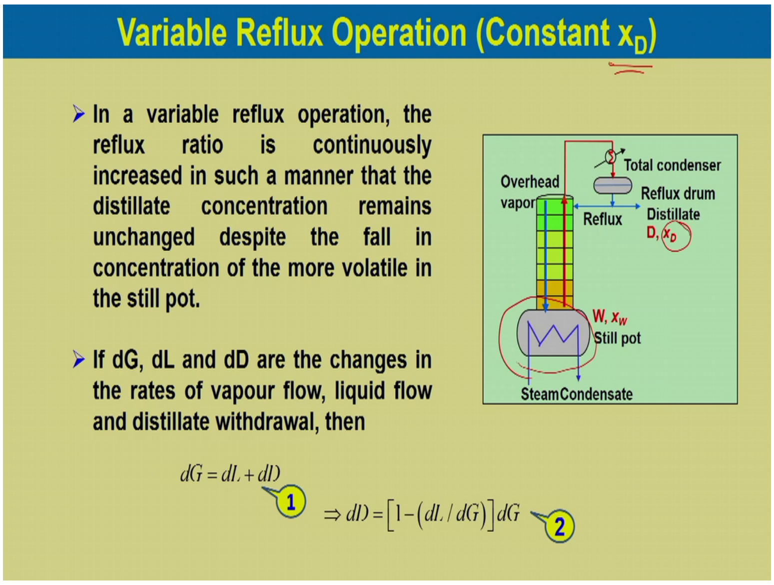

Now, let us consider the another case the variable reflux operation. So, in the variable reflux operation we keep the distillate composition constant that is xD is constant. So, in a variable reflux operation the reflux ratio is continuously increased in such a manner that the distillate concentration remains unchanged despite the fall in the concentration of the more volatile in the steel pot. So, since the reflux ratio is varied although the concentration on the steel pot over here is changing continuously, but the distillate composition xD remains constant.

Now, if dG dL and dD are the changes in the rates of the vapor flow liquid flow and distillate withdrawal, in that case we can write dG would be equal to dL plus dD. So, this is equation 1 and from here if you rearrange it would be dD would be equal to 1 minus dL by dG into dG. So, this is equation 2.

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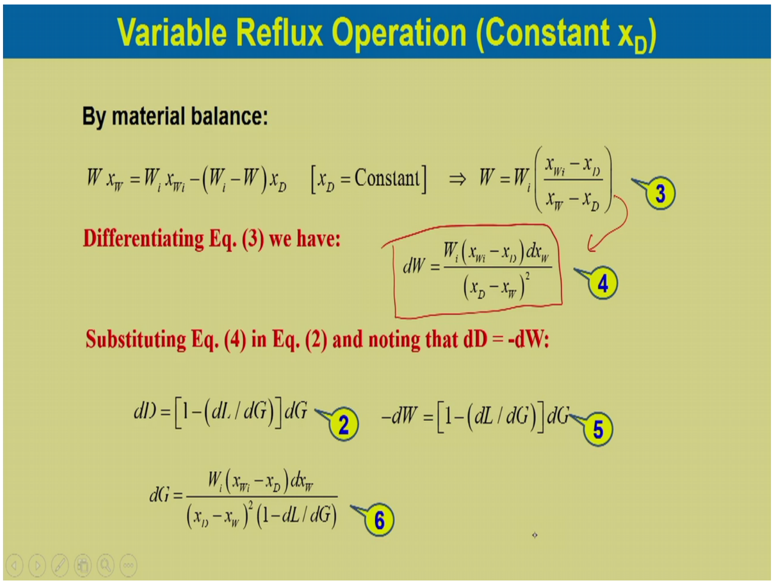

So, now, if we do the material balance in this case W xW would be equal to W i xWi minus W i minus W into xD. So, W i is the initial moles in the steel pot and its composition is x W i, W is moles in the steel pot and its composition is xW and xD is the distillate composition which is constant in case of the variable reflux. So, by material balance we can obtain this relation from here we can write W would be equal to Wi xWi minus xD by xW minus xD.

Now, if we differentiate this equation 3, we would obtain dW would be equal to W i xWi minus xD divided by xD minus xW square into dxW. So, this is the differential equation of the equation 3. So, this is equation 4 and if we substitute equation 4 in equation 2. Equation 2 is this one; dD would be equal to 1 minus dL by dG into dG. DD would be equal to minus dW.

So, if we substitute over here in this case equation should be minus dW would be equal to 1 minus dL by dG into dG this is equation 5 and if we just substitute this one dG would be equal to Wi into xWi minus xD into dxW divided by xD minus xW square into 1 minus dL by dG. So, this is equation 6.

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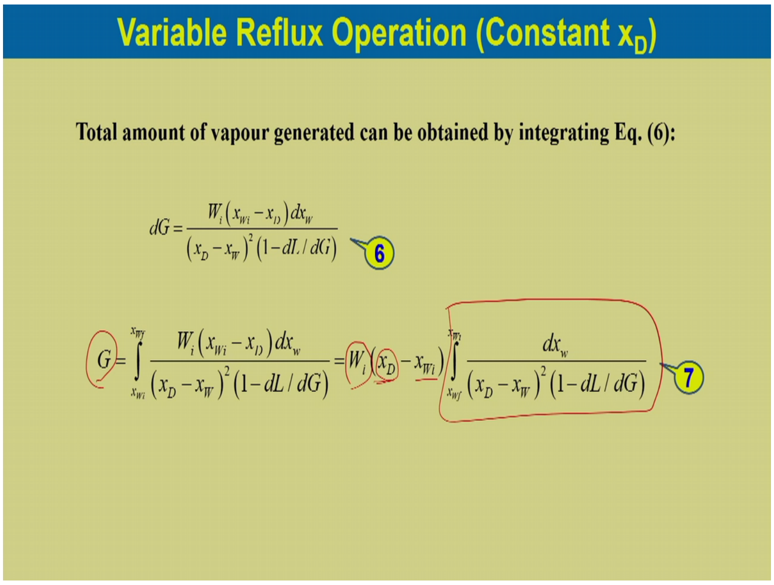

Now if we integrate this equation, we can obtain the total amount of vapour generated from the steel pot. So, during the distillation the amount of vapour which would be generated can be obtained by integration of equation 6. So, if we integrate G would be equal to integral xWi to xWf W i into xWi minus xD divided by xD minus xW square into 1 minus d L by d G into dW dxW which would be equal to W i xD minus xWi because these are the constant values initial and the distillate composition does not changes this is the initial mole.

So, these are constant quantities we have taken out from the integral and now these we have to find out this integral. So, this is equation 7 to calculate know the vapour generated in the you know distillation process for variable reflux with constant know distillate composition.

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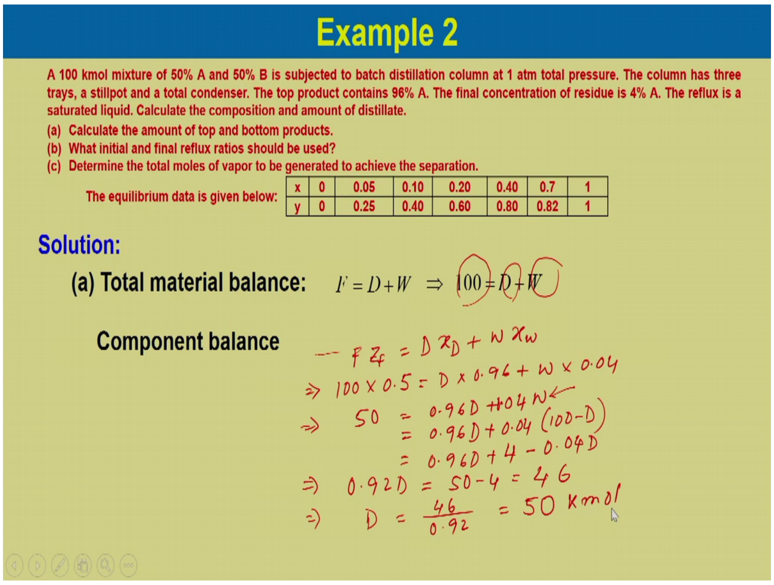

Now, let us take an example a 100 kilo mole mixture of 50 mole percent A and 50 mole percent B is subjected to batch distillation column at 1 atmosphere pressure the column has three trays a stillpot and a total condenser. The top product contains 96 percent A the final concentration of the residue is 4 percent A, the reflux is a saturated liquid calculate the composition and amount of distillate. So, that is one and another one is the amount of top and bottom products that is know distillate and the composition as well what initial and final reflux ratio should be used and determine the total moles of the vapor to be generated to achieve the separation.

So, to do that these are the equilibrium data which are given x and y. So, we can do the total material balance feed is equal to D plus W and we have feed 100 moles. So, distillate and the bottom; now if we do the component balance it is F ZF would be equal to D xD plus W x W. Now if we substitute the values feed is 100 kilo mole having composition is 50 mole percent A. So, it is 0.5 would be equal to distillate into its composition is 0.96 96 percent A and the bottoms final composition w into 0.04.

Now, this would be 50 which is equal to 0.96 D plus 0.04 W. So, if we substitute from the material balance substitute W with 100 minus D, it would be 0.96 D plus you know 0.04 into 100 minus D. So, in place of W we can substitute 100 minus D. So, essentially will get 0.96 D plus 4 minus you know 0.04 D. So, from here we can write you know

0.92 D would be equal to 50 minus 4 which is 46 and we can obtain D is equal to 46 divided by 0.92 which is equal to 50. So, the distillate is 50 kilo mole.

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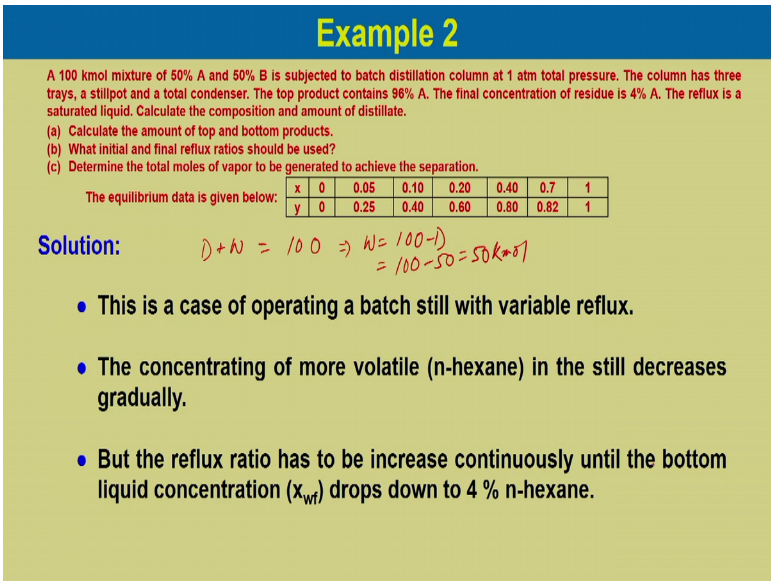

So, similarly we can obtain from the total material balance, we can write the D plus W would be 100 from here we can write W would be 100 minus D which is 100 minus50. So, 50 k mole is the bottoms. So, this is a case of operating a batch still with variable reflux the concentration of more volatile that is n-hexane in the still decreases gradually and but the reflux has to be increased continuously until the bottom liquid concentration that is x w drops down to 4 percent of n-hexane.

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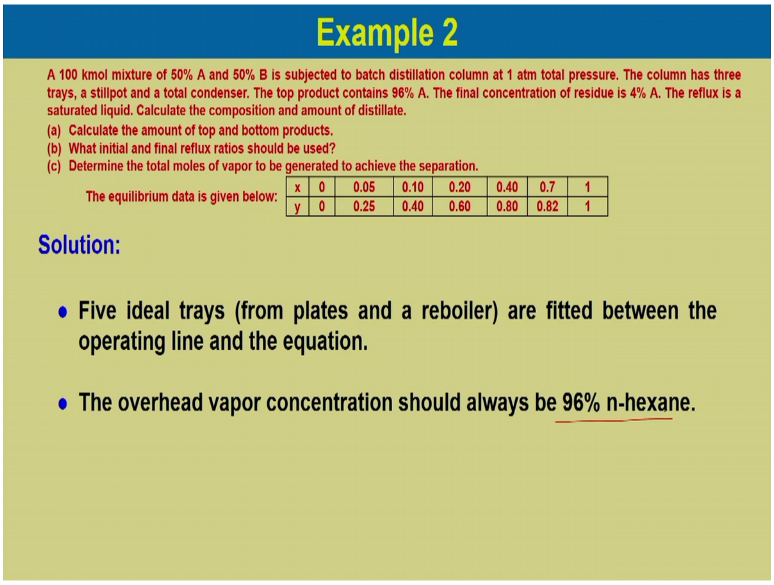

So, there are five ideal trays from the plates and a reboiler which is you know fitted between the operating line and the equation. So, you can see there are three trays, one stillpot and one total condenser. So, the overhead vapor concentration should always be 96 percent n-hexane.

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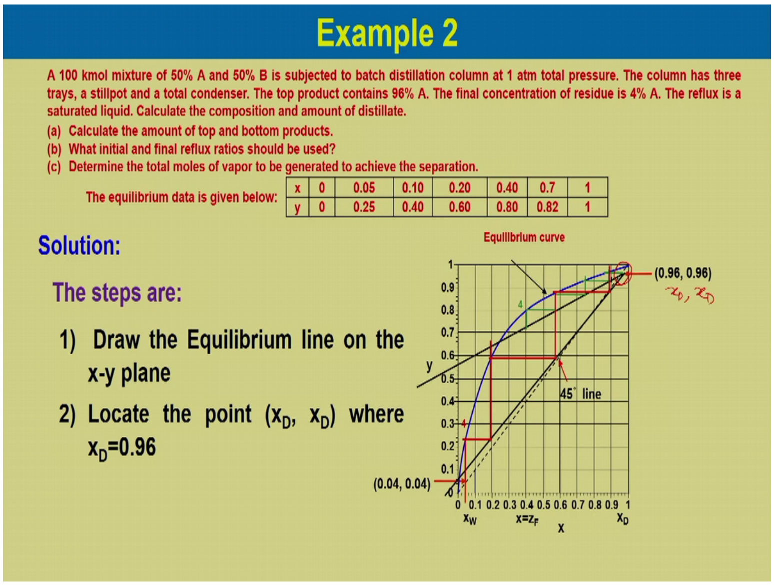

So, the steps to be followed here, draw the equilibrium line with the data which are given on the x-y plane. So, this is the blue line which is plotted over here and then locate the point xD xD where xD is equal to 0.96. So, you can see on the 45 degree diagonal this is the point xD xD.

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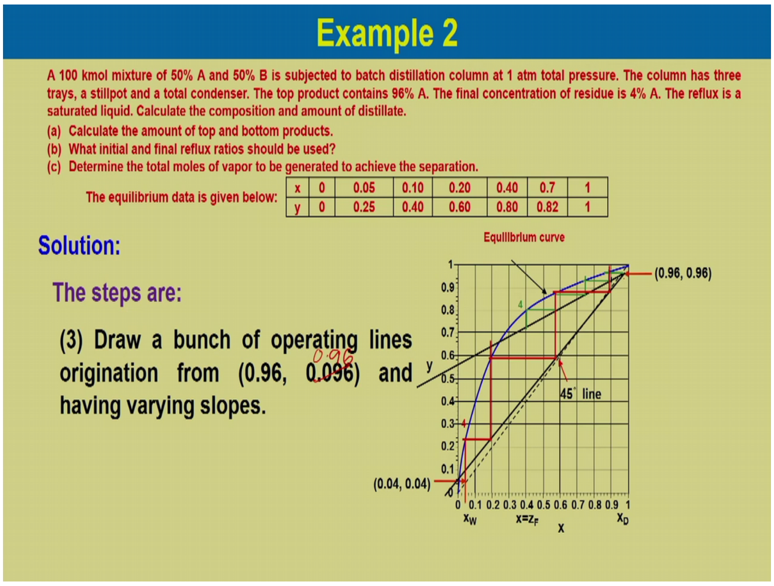

Then we have to draw a bunch of operating lines originating from this point. So, this is 0.96. So, originating from this point we can draw several operating line with a varying slope. So, slope will be different, but the composition at the distillate composition remain same, since you are varying the reflux ratio the slope of the operating line will change. So, you draw several operating lines we are starting from this point.

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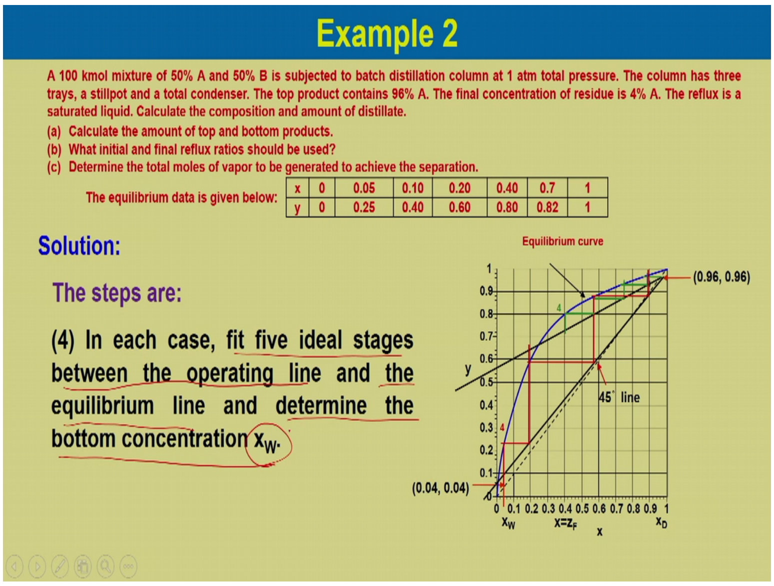

In each case fit five ideal stages between the operating line and the equilibrium line and then determine the bottom concentration that is xW. So, for each of the operating line we are starting from xD xD point and go to the equilibrium line and come vertically to the operating line and then equilibrium and vertical by stair case you know construction as we did for the McCabe-Thiele method, similar method has to be followed to go upto the five ideal stages and then obtain the values in the x axis the values of x W. So, each case the bottom composition can be obtained with different reflux ratio.

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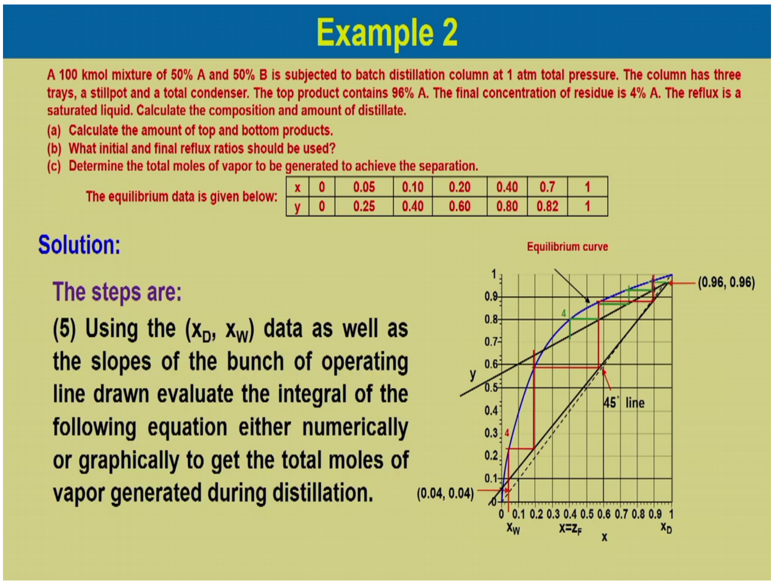

Using the xD and xW data as well as the slopes of the bunch of operating line drawn, evaluate the integral of the following equation either numerically or graphically to get the total moles of vapor generated during distillation.

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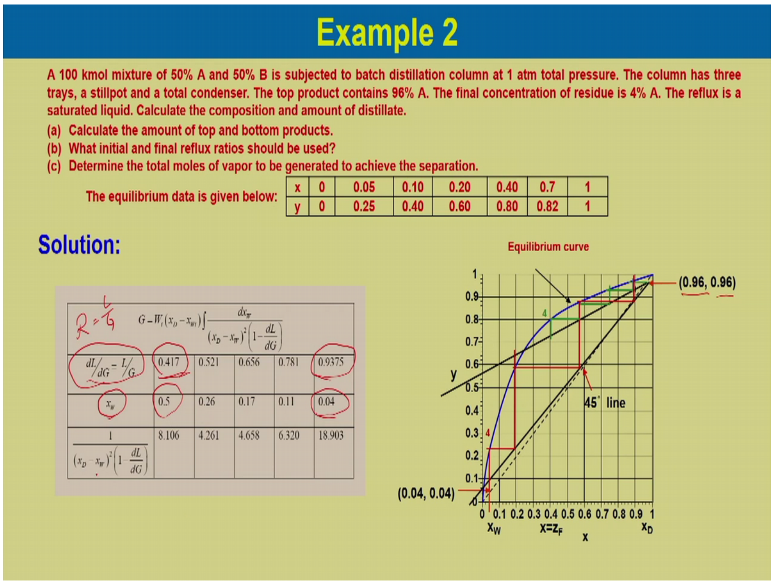

So, the equations which is known to you is G would be equal to W i into xD minus xWi integral dxW divided by xD minus xW square into 1 minus dL by dG. So, this dL by dG is L by G. So, this is the reflux ratio we maintain or we vary R is equal to L by G. You can see initial composition is 0.5 with respect to x W 0.5 we have to get for particular operating line having the reflux ratio L by G is 0.417. So, with respect to 0.417 we will get x W is 0.5. So, once it is known and then xD is fixed 0.96 and 0.96.

So, you can calculate from this 1 by xD minus xW square into 1 minus dLby dG. So, dL by dG is from here from the reflux ratio you are varying and that for each case what you are doing you will draw five ideal stages to obtain the bottom composition xW. So, this is the range of reflux ratio you could see that is the initial reflux ratio is 0.417 corresponding to xW is equal to 0.5 and finally, you will obtain xW is 0.4 percent in the residue. So, 0.04 corresponding to the reflux ratio or L by G is 0.9375. So, then you have this data.

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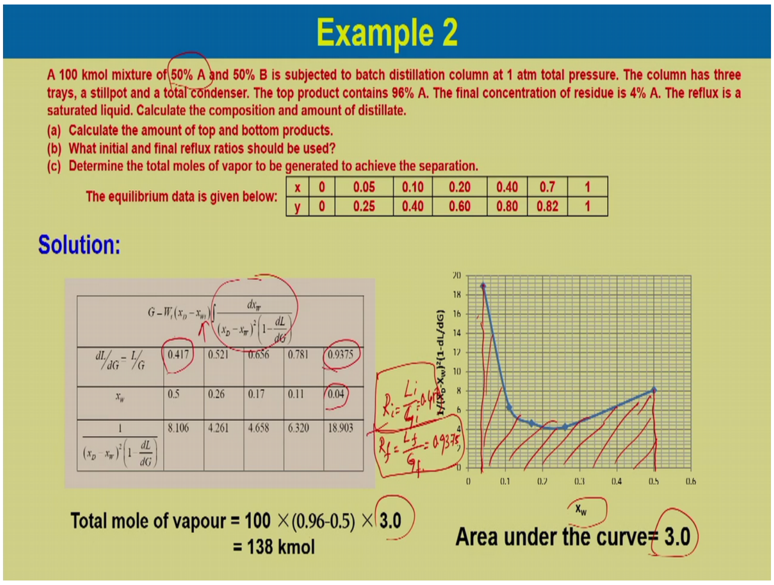

Now, you plot this 1 by xD minus xW square into 1 minus dL by dG versus xW. If you plot you will get this type of figure and this is from 0.04. So, this is upto from this line. So, you need to calculate the area under this curve graphically and if you just get area under the curve. So, then you can just multiply with W i into xD minus x W i xD is known and xWi is also known to you.

So, the area under the curve from here you can calculate approximately 3 and you can calculate the total mole of vapor which would be generated would be equal to 100 into 0.96 is the distillate composition 0.96 xD minus xWi is you have a 50 mole percent A. So, xWi is 0.5 into the area under the curve which is 3. So, if you just multiply then it will give you 138 kilo mole.

So, the total mole of vapor which would be generated is 138 kilo mole. We have calculated the top and bottom products, the initial and final reflux ratio this is the initial reflux ratio it is W i this is R i initial reflux ratio corresponding to xW is equal to 0.5 is L i by G i and corresponding to the final reflux ratio corresponding to xW is equal to 0.04 which is Rf would be equal to Lf by Gf. So, which is you know 0.9375 and this is you know 0.417.So, the initial and final reflux ratio you can calculate and you can calculate the total mole of vapor which is generated for this distillation operation.

So, thank you for attending this lecture and we will continue few more lectures to complete our distillation operation.