Mass Transfer II

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Module No. # 01

Lecture No. # 23

So, in the previous lecture, we completed our discussion on McCabe-Thiele methods, how to construct y versus x diagram along with this operating lines, q line and determine the number of stages. So, in today's lecture we will take an example on McCabe-Thiele method, very similar to what we had in case of Ponchon-Savarit method. So, very simple configuration, we have the distillation column feed making an entry; you have the two products, we know the compositions, we know the molar flow rates of the three streams, then we will like to determine - how many number of plates are required, what is the q line, how to draw operating lines? So, let us take this example on McCabe-Thiele method.

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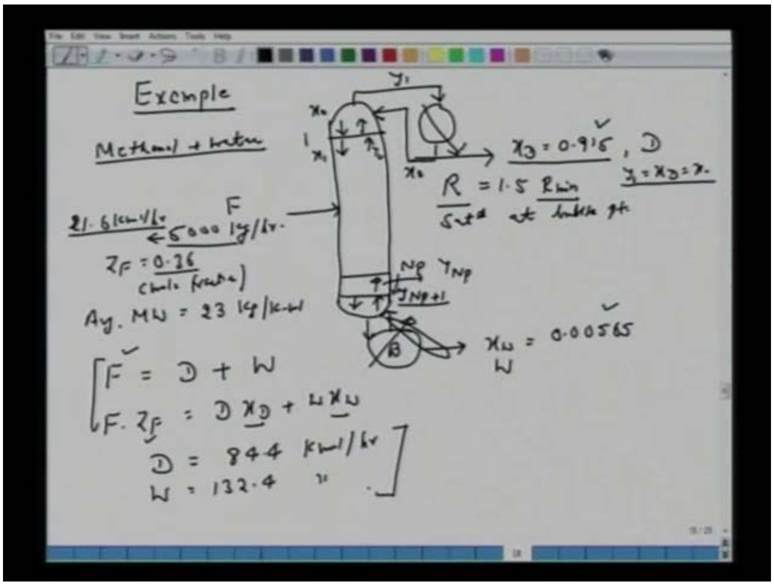

So, let us draw a schematic of this distillation column, we have, let us say, top product, and then we have total condenser. Let us say that the reflux is saturated, it goes back to this top of this plate here.

So, we have feed entry; similarly ,we have here reboiler; then we have this vapor reflux going back to this distillation column. And let us say, that in this example, we have this methanol plus water. Say the feed flow rate is 5000 kg per hour and the mole fraction is given as Z F 0.36. So, it is a mole fraction. So, based on this 0.36 recall ,you know earlier example, we had the… we can calculate the average molecular weight.

So, which is say, 23 and based on this, ao, this is 23 kg per kg kilomole and we can convert this 5000 kg per hour into 21.6, say kilomole per hour. So, this is a good practice to convert of this weight flow rate into this molar flow rate which is 21.6 kilomole per hour; then it is given that we have this top product, which is mole fraction is 0.915 and we have this D kilomole per hour. Similarly, the bottom product is Xw, mole fraction is given as 0.00565 and molar flow rate is W here. It says that reflux is 1.5 times this R minimum and this reflux is saturated at bubble point. So, the saturated feed now, saturated reflux is sent back the top column one. So, if this is x D total reflux, this is y 1, we know this is x 0. So, y 1equal to xD equal to x 0, we have total reflux and then we have this two streams, this is x 1, this is y 1 and we have y 2; this is your x D or x 0 and so on and so forth.

Similarly, the top bottom column, bottom plate; this is y NP plus 1. So, this is a composition. So, the vapor which would be in equilibrium with this bottom product, and then you can construct, similarly, you know mole fractions with the two; let us. So, this is y NP plus 1; this would be y NP. So, this is NP NP, and then we have NP minus 1 etcetera. NP plus 1 here reflux boiler.

So, before we start, we solve the solve or redraw the y versus x diagram; let us calculate the unknown quantities like F; given F, what are D and W? So, we have F equal to D plus WF into ZF equal to D xD plus WXW. So, F is given ZF mole fractions 0.36, xD is given as 0.915, XW is given as 0.00565; two unknowns, two equations. One can solve to get the top product as 84.4 kilomole per hour and we have this bottom product as 132.4 kilomole per hour.

So, now what we have to do is, in this we should draw y versus x diagram, maybe we have been given T x y diagram. So that we know, what is a temperature corresponding to this feed state, where the feed is saturated, what is the boiling temperature? The feed is cooled, where is the location of your enthalpy? Or the location of this, what is the temperature of the feed, etcetera.

And here again, if you recall the discussions, while drawing the operating lines, there are three options , you have to see if you know the q lines, and if you know one of the two operating lines, the third can always be drawn here. Now, in this case again, we have to determine what is this q line? So, let us see if you can determine or how do we determine this q line?

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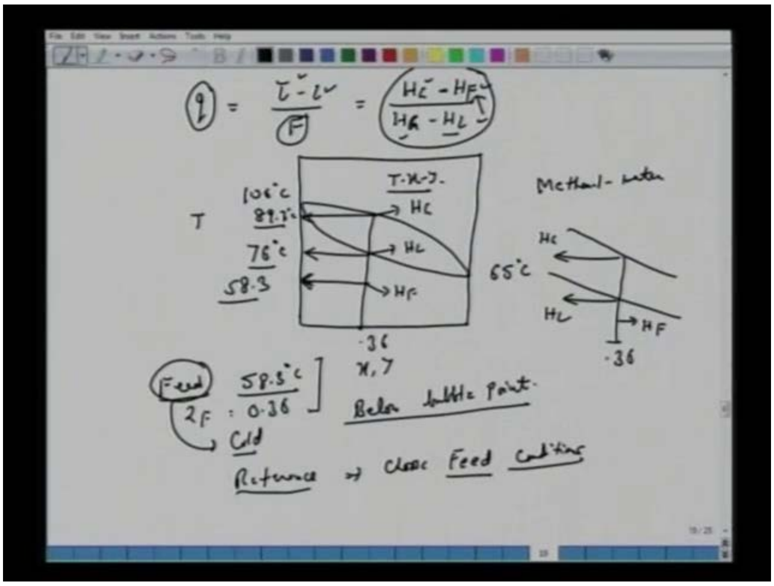

$$q = \frac{\bar{L} - L}{F} = \frac{H_G - H_F}{H_G - H_L}$$

So, the definition for this q is L bar minus L over F which is also same as H G minus HF over H G minus H L. So, which means to obtain this q line, one needs to calculate, these coordinates. So, generally where some data would be given to us, the first thing is that we have been given this T x y diagram for methanol water system. So, methanol is more volatile than water; its boiling temperature is 65 degree centigrade, your component here, and here, we have this 100 degree centigrade. Now, mole fraction is 0.36. So, from this diagram, it is easier to find out what would be the boiling temperature of this feed mixture.

So, from here if you look at the curve for this T x y diagram, you can obtain from you can obtain from, one of the handbooks, you know, for thermodynamics or even Treybal or McCabe-Smith, they report T x y diagram for methanol-water system, one can obtain this, one can draw this T x y plot. And in this case feed is given, heat temperature is given as 58.3 degree centigrade and composition was given to us as 0.36.

Now, from here you know we look at this T x y diagram; that means, here feed temperature is 85.3, which means we can say that the feed is cold. So, what I am trying to say here that looking at this T x y diagram, one can obtain this status of this feed; this feed is actually cold here or it is below this bubble point, below a bubble point. So, now, we have to calculate this quantity to obtain this q line.

So, although F is given, but we are not in we are not in position to obtain L and L L bar, because we do not know the reflux ratio which is at actually 1.5 times, R min; to obtain R min one has to obtain this q line, but now from the enthalpy data one can obtain this quantity, one can evaluate this quantity. So, look at the here we have H G minus HF. So, the saturated vapor enthalpy minus feed enthalpy, then we have saturated enthalpy of the vapor minus saturated enthalpy of this liquid.

So, this is what we trying to say, that if you extend this line, this temperature is 89.7 degree centigrade. So, this quantity will corresponds to H G, this is HF and here we have this H L; of course, this is a T x y diagram corresponding to this, we will have this H H HGHF diagram which means for this composition of 0.36 this is H L, and this is H G, and feed is somewhere here. So, now all we have to do is actually realize that we have to take a difference H G minus HF, H G minus H L. So, whenever we have this difference best thing is that one should define this reference enthalpy or reference conditions, and the most simplest would be if you can choose feed, because the status of feed is known here, choose feed condition as the reflux.

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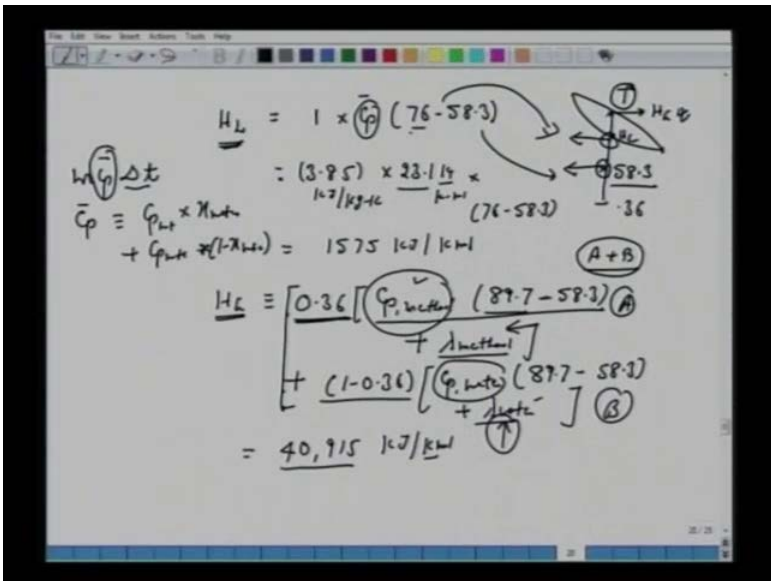

$$H_L = 1 \times \bar{C}_p (76 - 58.3)$$

$$= (3.85)\,\text{kJ/kg-K} \times 23.1\,\text{kg/kmol} \times (76 - 58.3)$$

$$m \bar{C}_p \Delta t$$

$$\bar{C}_p = C_{p,met} \times x_{meth} + C_{p,wat} \times (1 - x_{meth}) = 1575\ \text{kJ/kmol}$$

$$H_G = \left[0.36 \left[C_{p,methanol} (87.7 - 58.3) + \lambda_{methanol} \right] + (1 - 0.36) \left[C_{p,water} (87.7 - 58.3) + \lambda_{water} \right] \right]$$

$$= 40{,}915\ \text{kJ/kmol}$$

That means, H L if I write as 1 mole multiplied by C p into 76 minus 58.3. So, go back to the previous diagram for this T x y diagram. We have boiling temperature is 76 and the feed temperature is 58.3. So, this is 58.3 and this is 76. So, we are trying to calculate H L. So, H L with HF as a reference, we need to know the specific heat of this mixture of 0.36. Let us assume that these quantities are known to us. So, we can obtain H L, we can calculate H L from here as 1 into Cp bar 76.583; given the values of Cp bar as 3.85 which is kilojoule per kg per Kelvin. So, this data is given to us, we multiply by the molecular weight, which we had calculated in the beginning 23.1 k g per kilomole multiplied, we have this 76 minus 58.3 degree Celsius difference, same as Kelvin, to obtain H L has 1575 kilojoule per kilomole.

So, we have calculated this H L. Similarly, we can calculate H G. Now, again if you recall our discussion when we started this distillation column for the vapor enthalpy, which is here H G, one assumes that two components, A plus B both of them are heated, separately to this temperature, vaporized and then they are mixed. So, to obtain this enthalpy of this H G; that means, this composition of water and methanol 0.36, it is a mole fractions for larger relative volatility of more volatile components, which is methanol here, the boiling temperature of methanol is smaller than the water. So, we have 0.36.

Now, we have C p methanol into 89.7 minus 58.3. So, this 89.7 correspond to this temperature which is a dew point temperature, and we have 76, if you said here is bubble point temperature and this is the feed temperature. So, when we are writing like this C p methanol 89.7 minus 58.3; that means, so much mole fraction of methanol is heated from here, all the way till this dew point, then it is vaporized, lambda methanol and then they are mixed with water with water. So, this is the calculations, if you should recall go back to your previous lecture notes C p, what calculate H G and H L? So, we have 89.7 minus 58.3 plus lambda water.

So, again make a note that how we are calculating H L and H G. First, we have chosen the reference, which is like for our convenience, we have chosen feed temperature of feed enthalpy as our reference temperature. So, what is H L saturated liquid? All right, of this mixture is 76 minus 58.3 degree centigrade. So, m C p del t. So, del t we know 76 minus 58.3 C p bar, we have to calculate based on this average C p, for the two the two components methanol and water. So, we will have situations like C p bar equal to C p of water multiplied by the mole fraction of water plus C p of methanol plus 1 minus x into 1 minus x water. So, we calculate H L to calculate H G, one is to assume that the two components - A and B, they are heated till the dew point. So, in the same proportion 0.361 minus 0.36; they are heated as if separately, then vaporized and then are mixed. So, we have this H L. So, all this quantities are given to us assuming, suppose we obtain 40, 915 kilojoule per kilomole.

So, you look look at the handbook to obtain this physical, or thermodynamic properties of methanol, and water here, latent heat of vaporization for methanol - pure methanol - latent heat of water say at 1 atmosphere, then do these calculations to obtain this H G. So, now, we have H G, now we have H L, we can calculate our reflux ratios. So, sorry we can calculate q here, q line.

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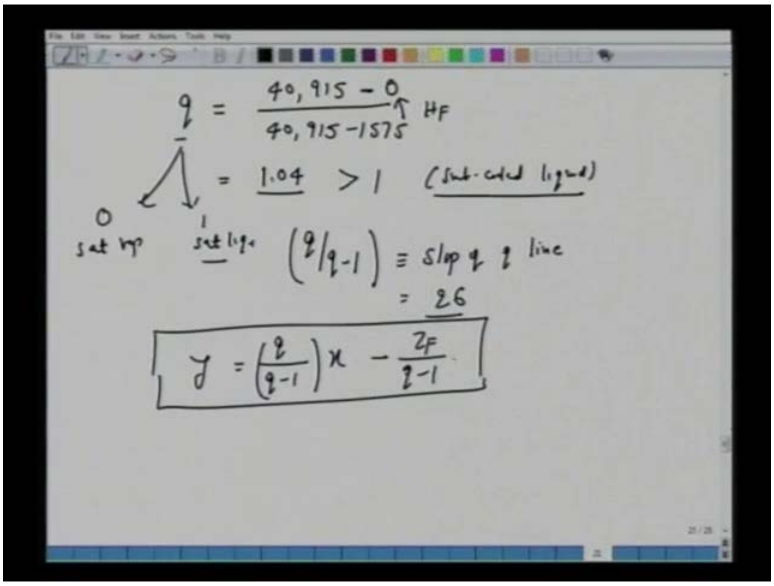

$$q = \frac{40,915 - 0}{40,915 - 1575} \uparrow HF$$

$$= \underline{1.04} > 1 \quad (\underline{\text{Sub-cooled liquid}})$$

0 sat vap

1 $\underline{\text{sat}}$ liq.

$$\left(q/q-1\right) \equiv \text{slop of } q \text{ line}$$

$$= \underline{26}$$

$$\boxed{y = \left(\frac{q}{q-1}\right)x - \frac{z_F}{q-1}}$$

So, q is H G 40915 minus 0. So, that is HF reference, because all we require is a difference, both in numerator, and then, denominator 40915 minus 1575. So, now, we have this q as 1.04. So, it is very important that we realize here that first quantity we have to evaluate is q.

So, once we have this q and its 1.04, recall it is greater than 1, then we have sub cooled liquid. So, recall our earlier discussions, when q assumes different different values, the most common was 0, then we have saturated vapor, we have 1, when it is saturated liquid then we address different different quantities, different different situations like q greater than 1 for sub cooled liquid, q less than 1 was superheated etcetera. So, once we have q, then we can obtain the slope of q line. So, which is q over q minus 1, So, this is slope of q line, and if you put this quantity here, you can obtain 26. So, now we have this q line equations, recall y equal to q over q minus 1 into x y equal to m x plus intercept which is at minus ZF q minus1.

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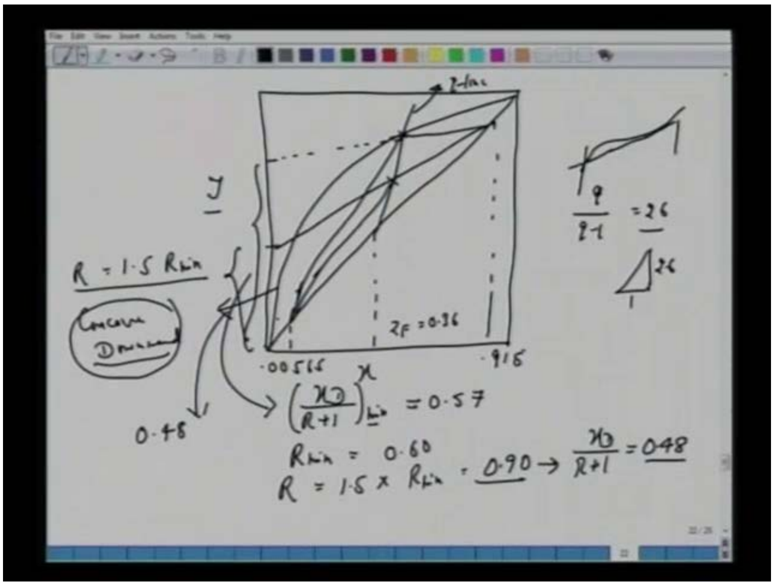

$\left(\frac{x_D}{R+1}\right)_{min} = 0.57$

$R_{min} = 0.60$

$R = 1.5 \times R_{min} = 0.90 \rightarrow \frac{x_D}{R+1} = 0.48$

So, now knowing q knowing this ZF, we are in position to draw this q line or mark different different coordinates on y versus x diagram. So, we have y, we have x, from T x y we can also obtain this y, y x diagram or may be this y x diagram is given to us. So, let us draw qualitatively. You can always go through this methanol water system in some handbooks and can do this, can complete this exercise. So, now we have this xD 0.91 y, and we have here 0.00565 R is given to us that R is 1.5 times R minimum.

So, first we have to obtain 1.5 R min, feed is ZF is 0.36. Now, we know the slope of this line q over q minus 1 as 26. So, we can take this slope 26 at 1 or we can obtain tan theta, and find 10 theta, to draw this q line. So, notice this slope of q over q line minus 1 is greater than 1, q is greater than 1, we have this line going like this with the slope of 26. Now, we have 0.915 here, 0.05165 here, this curve if you look at, now for this methanol water system, is concave downward, which means to obtain this minimum reflux, we can connect with this ,we can connect with this. We said in the earlier class that if the curve is say non-ideal, if the system is non-ideal, then there is a possibility that this line - operating line - can make a tangent ahead of this intersection anywhere on this curve.

But, in this case this curve is concave downward. So, all we do, we intersects, we extend this q line, this q line and its intersection on this equilibrium curve, we connect these two lines. Now, if you extend this, so, here that it is inch carrying force is zero, take this slope or intercept, you take this intercept which is xD over R plus 1 min; min, corresponding to this minimum reflux; if you do this, this quantity can be shown to be equivalent to 0.57; from this one can calculate R min which is 0.60, and once we know R min, now we have operating reflux as 1.5 times R min which is 0.90.

Once we have this operating R, then we can find out intercept, the operating line as 0.48. So, all it means the different ways of drawing the new operating lines; once we have the new intercepts 0.48, we can go back to this and mark 0.48; then if you connect with this, now, we have the new operating lines; q line will remain the same, and wherever it intersects, now we can now connect with this, let us draw it again.

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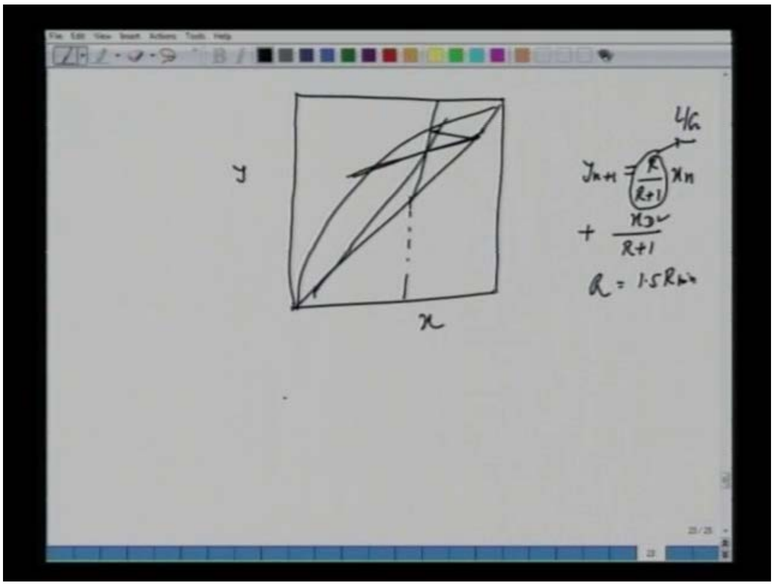

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$

$$R = 1.5 R_{min}$$

So, here we are trying to say that, we know the equation of two operating lines. So, this is y, this is x, we have y versus x equilibrium curve, operating line for the top column or enriching sections, we know y n plus 1 over R over R plus 1 x n plus we have xD over R plus 1, R over R plus 1 is same as L over G.

But, we cannot use this operating line, because we do not know the reflux ratios although we know this top product, but here it was given to us that R is 1.5 times R min. So, started from here, we can go like this; in our case, it was given that q line is given, we cannot we could not draw this line, you could not draw this line, but in our case, this q line was given, so, what we did, we first we drew the q line, then we looked for this line for this R reflux, R minimum reflux ratio.

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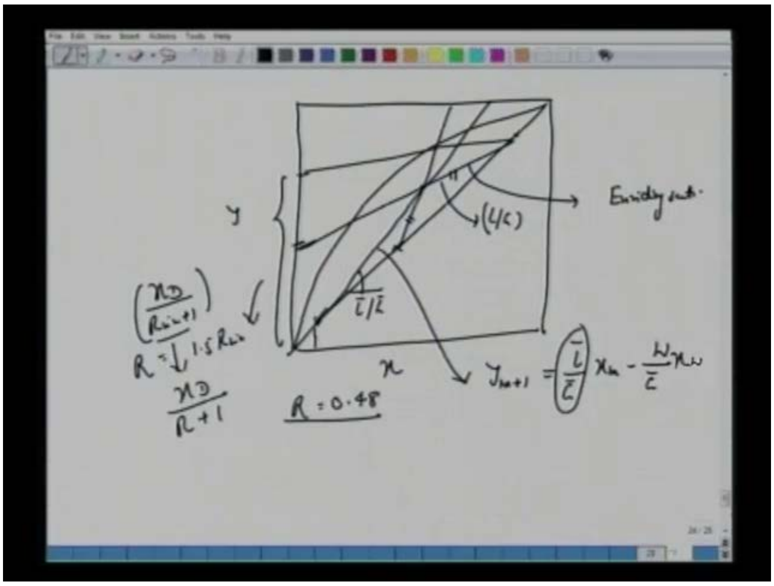

So, essentially what we have y versus x, at 0.36 we have this q line, here we obtain this R min. So, corresponding to this intercept xD over R min plus 1, we obtain R min; then we had 1.5 times R min, then we had xD over R plus 1, and then, we get the new intercepts; this new intercept will give us the two operating lines. So, now once we have this second operating line, remember we did not solve explicitly the equation of this second operating line or for the equation for this enriching sections, sorry stripping section is L over G bar Xm minus W over G bar, but we do not know these quantities, W over G. So, all we did first we had the q line, then we got this R or the equation for this enriching section.

So, whenever we have, once we have these two - this line, this line - it intersects here, now we can connect with this. So, we have this new line equations, from this, of course, we can find out L bar by G bar, here also we have L by G. So, once we know the reflux ratio here R, which we calculated as 0.48, we can calculate the amount of the liquid or amount of the vapor flowing in this distillation column.

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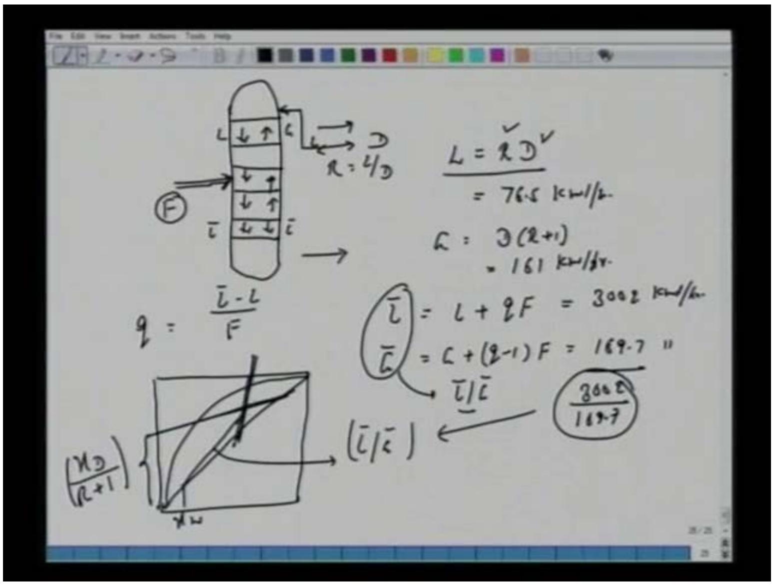

So, if you have the distillation column like this. So, we have this F top product, bottom product and we have these are the trays here. So, we have L, we have G, we have L bar, and we have this G bar, and this is a reflux here. Reflux ratio is L over D. So, this L going to into into this. So, all we can say that R equal to R into D, which is we know the reflux ratios 0.48, we know the top product quantities D which we calculated, multiply we multiply these two, you will get 76.5 kilomole per hour, G D into R plus 1 just a material balance, we have L, G and D going out here, G equal to D R plus 1, we have put the quantities to obtain 161 kilomole per hour.

Now, what happens to L bar? What is L bar? Recall the definition for q; L bar equal to L plus q F. So, go back to the definition q, q equal L bar minus L over F. So, we have feed entry here. So, this is L bar, this is L, and recall we had similar cases, where the feed was cold, feed was saturated liquid, feed was saturated vapor, and then we talked about different amount of different q(s), different values which you can assume here. So, in this case L bar is L plus q F, you put this quantity here, we should get 3002 kilomole per hour.

Similarly, we can obtain, calculate, G bar; this G bar would be G plus q minus 1 into F, which is 169.7 kilomole per hour. The idea here is that, if we calculate this L bar by G bar, you should be able to convince yourself that this is the ratios of the operating line for these enriching sections; in other words, we had q line like this; we have the operating line like this. So, we could draw this line, because we knew the values of q, q over q minus 1 and we calculated the new intercepts based on the reflux ratio which was 1.5 times the minimum reflux ratios. So, we had this operating line, and we have this q line, if you connect it with XW and calculate this reflux ratios, you must get the same number as what we obtain here 3002 over169.7. So, from here or from the geometries, you must get the same results.

So, we are trying to make a point here, that there are several ways of calculating these quantities here, knowing the two reflux, knowing the two operating line, one can also obtain this q line. Now, we can draw, now we can draw, the y versus x diagram again to calculate the total number of plates, which is a straightforward here. Now, we have total condenser case here.

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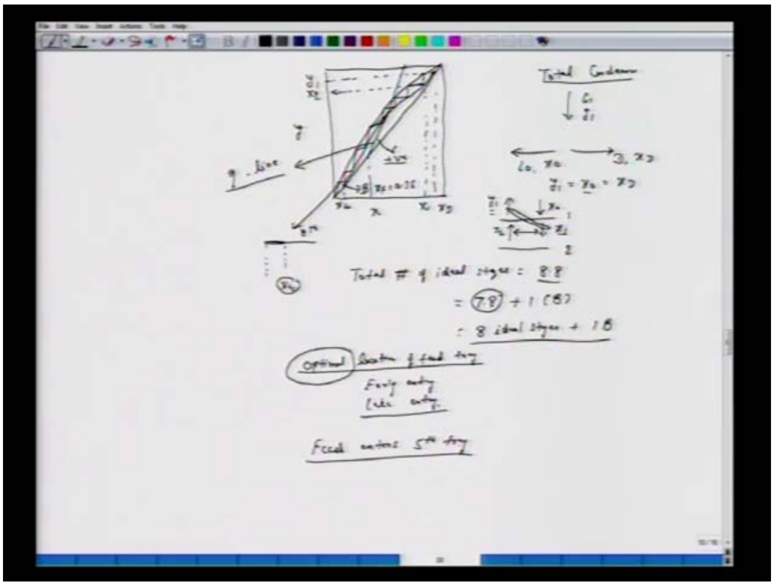

So, let us draw y versus x equilibrium curve here. So, we have y versus x, let us say this is 45 degree line here, and we have the equilibrium curve like this, XF was given as 0.36. So, let us mark XF, we have xD, we have this is xD here, and we have this bottom product as xW. So, in case of total condenser, what we have the vapor flow rate, let us say G 1 composition is y 1, entire vapor is condenser and the product part of this product which is D xD, so, it is sent back as a reflux.

So, we have L 0, the composition, let us say, this is x 0 here. Now you can see that since a total condenser y, one will be same as x 0 and it will be same as xD. So, in other words, if we have trays, let us say top tray 1 and 2, we have this composition of the liquid reflux x 0, the vapor, which is leaving tray one is y 1; same vapor goes to this total condenser. So, if this is x 1, y 1 and x 1 will be in equilibrium and y 2, and we have x 1 connected through this operating line.

So, let us try to mark these points here, on this equilibrium. So, starting with x 2, xD here which is same as x 0, we have from the 45 degree line, this coordinate is y 1; now, y 1 and x 1 they are in equilibrium, two leaving the streams. So, we have, we can have this x 1. Now let us draw this q lines, operating lines, we have the positive slope of this say q line. So, let say this is your q line, and if you draw the first operating line like this, second operating line, let us connect it like this here. So, keep this in mind that the slope is positive of this q line.

So, now, we have y 1 and x 1 we marked here, x 1 to y 2 we can get. So, this is when this is x 1, now, we have this from the operating line, we have this x 2. So, this way we can draw, we can start drawing the stages 1, 2, 3 etcetera, and as soon as we cross this q line, then we step down to this second operating line, and then, we can proceed here for the rest. If you draw this carefully, you will see that we require stages slightly greater than 8; in other words, if you expand the last stage, then we have if this is your XW, one will have to the 8th stage, one will have to exceed this mole fraction at least this XW by some amount. So, in this case, if you mark all the stages, you will see that total number of ideal stages or theoretical stages will come out to be 8.8. So, you must not forget that this 8.8 consist of one boiler. So, the last stage, whatever you have drawn here will be this boiler here. So, when we say 7.8, we can say that approximately, we require 8 ideal stages plus 1, we have this ready boiler here.

We must remember one more thing important here, that we are talking of this optimal location of feed tray. So, if you remember in the previous lecture, we talked about early entry and we talked about late entry. So, in this case or we are saying that as soon as you come, cross this q line, which is drawn like this. You must step down to this second operating lines. So, what we are trying to say here that, once you cross this q line, you have to step down to the second stage for optimal location of trays. In this way if you are careful, you will say that the feed will enter or if it enters fifth stage, fifth tray, count it from top.

So, what we do next is we define efficiencies. So, if you recall from our previous discussions, we say that if we choose any stage, we assume that the vapor leaving that stage is in equilibrium with the liquid leaving that stage.

So, it is an ideal situation and we have number of trays or any trays call it theoretical tray, but in reality, because of so many non-idealities you know like frothing or you know non-uniform mixing, there is a possibility that the vapor the liquid leaving, they are not in equilibrium. So, in those cases one has to define for few efficiencies, the overall efficiencies, essentially, physically we are trying to say that if there are non-efficiencies in the column, then we require more number of stages or more number of trays; instead of 40 trays, you know efficiency is 0.8 overall; then it is 40 by 0.8; we require larger number trays to have that separations.

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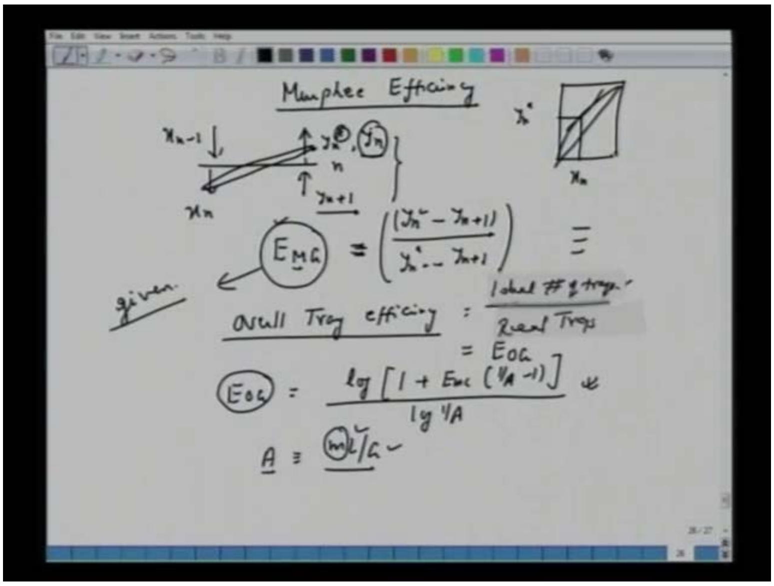

Murphee Efficiency

$$E_{MG} = \left(\frac{y_n^* - y_{n+1}}{y_n^* - y_{n+1}}\right)$$

Overall Tray efficiency : $\frac{\text{Ideal \# of trays}}{\text{Real Trays}}$ $= E_{OG}$

$$E_{OG} = \frac{\log\left[1 + E_{MG}\left(\frac{1}{A} - 1\right)\right]}{\log \frac{1}{A}}$$

$A = mL/G$

So, we like to define this quantity here, feed Murphree Efficiencies. So, Murphree efficiency, we also use in our first introductive lectures, when we talking of cascades and stages. So, what essentially we have is y n, let us say nth stage and we have this x n. So, this quantity is y n plus 1 and we have this x n minus 1. So, these two are in equilibrium; if they are in equilibrium let us put a nomenclature star here, y star. So, this is a theoretically it is an ideal situations, we have 100 percent efficiencies, then y n star and x n, they will fall on this y versus x diagram.

So, given x n, we have this y n star, but now we are saying that it is, this two streams may not be in equilibrium; that means, we have y n less than y n star. So, all now we can define Murphree efficiencies with the nomenclatures EMG, E for Efficiencies, M for Murphree, and G for the vapor or the gas phase. So, we have saying that, now efficiency is y n minus y n plus1.

So, this is the actual enrichment composition of this vapor deriving this plate is y n plus 1, it is enriched or increases to y1. So, this is what we are getting really, in a real sense, but actually, the ideally would have been y n star minus y n plus1. So, y n is smaller than y n star, that is why we have these efficiencies at right. So, this is the quantity, one has to evaluate for each tray, but now it is very difficult in the sense that, we do not know the compositions of y n at every trays.

So, this number remains the theoretical number, one has to obtain you know some some correlations. Similarly, we can define as another way of efficiencies, which is like over all tray efficiency, which is nothing but ideal number of trays over how many number of trays we have and this this is as a nomenclature EOG. One can show that or it has been shown that EOG is related to this EMG as, log 1 plus EMG 1 over a minus 1 over log 1 over A, where A if you recall we use this letter in case of absorptions column as as well we have m L over G. So, this definition remains the same except, now m is the slope of this equilibrium curve y versus x. L and G are the molar flow rates. So, this one correlation we have between overall efficiencies and the Murphree Efficiencies, as we said earlier the Murphree Efficiency has to be defined for every plates,which may not be possible. So, very often we work on these overall tray efficiencies which is nothing but total number of trays required or the adjusting trays over this ideal number of trays here.

But suppose if EMG is given to us, because there are ways to calculate EMG from some correlations. So, if EMG is given to us; that means, we should be able to work out or find out what is the adjusting composition of this y n; that means, we have to draw quantity like or the equilibrium curve like this pseudo equilibrium curve.

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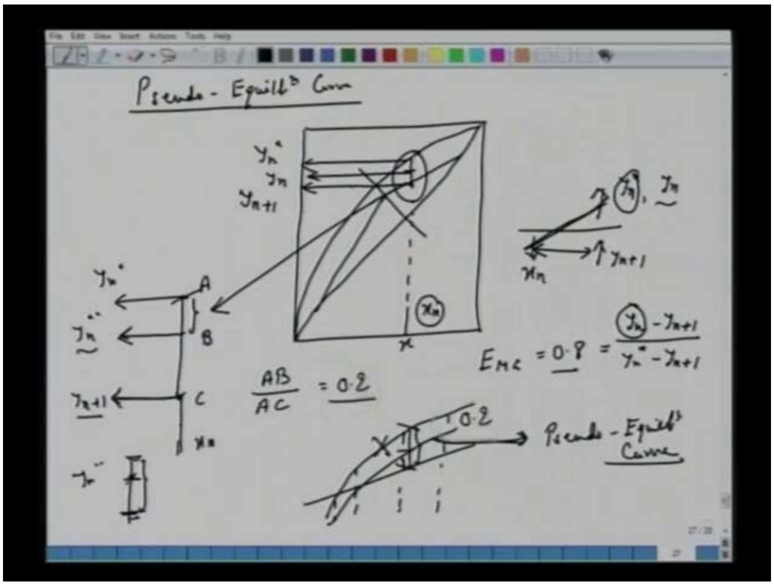

Because, now we are talking in terms of efficiencies inefficiencies. So, pseudo equilibrium curve, let us assume that Murphree Efficiency is given to us. So, now, we have this y versus x diagram; let us say this is the q line and we have this another operating lines. And let us choose, we have this at certain locations, say we have this x n. So, now, this x n is in equilibrium with now y n star, and the operating line if we recall from our discussion, will give you y n plus 1.

So, we have x n and now we have this y n plus 1. So, but now we are saying that because of these efficiencies , these leaving streams y n is not in equilibrium with this x n. So, we have this tray here, this is y n, this is y n plus 1, we have this x n. So, x n y n plus 1 are connected by this operating line; given x n, what is y n plus 1 from here and given x n we should have y n star, if the two streams are in equilibrium. So, if the efficiencies or Murphree Efficiency is given as 0.8. So, all it means this 0.8 equals y n minus y n plus 1 over y n star minus y n plus 1. So now, coming back to this diagram here, we should realize that now instead of y n star we have y n. So, if you expand this line here - vertical line here - now we have let us say a for y n star, that is ideal situations, y n star is in equilibrium with this x n, and x n and y n plus 1, that is a composition we obtain from the operating line equations, and now, we have this 80 percent efficiencies.

So, instead of y n star, now the composition of the vapor leaving the tray is y n; that means, if you mark this as A, C, B, A B over A C is 0.2. So, which means if we have this equilibrium diagram like this, you are supposed to choose several of this x 1, x 2, x 3, and then, take an offset at 0.2 from each of this curve. So, we will have to draw again the two operating lines like this; take a point come to this operating line take an offset of 0.8 from here come to this operating line measure this by scale 8.8, come down to this; essentially, we have created an pseudo equilibrium curve. So, you must understand the physical meaning of this, the vapor which is leaving this tray should have been saturated, but it is not saturated here, because of certain efficiency factor which means y n; now, one has to calculate equivalent to this condition here 0.8.

So, from operating line we just mark any x n mole fractions, we obtain y n plus 1, and the equilibrium curve gives y n star, y n star here, y n plus 1, measure this scale 0.8, 0.7 whatever is given to us. Now, we get y n say double star. So, it be our pseudo equilibrium curve. So, we have to go to the next point, we have x n, you obtain equilibrium curve y n star, you have this operating curve for this y n plus 1, measure this, take this offset we have another point here as y n star here, connect all of this to obtain this pseudo equilibrium curve that becomes our starting point and from here onward we can do all of our calculations; we can then we can forget top one.

So, now what we do here we take one more example of this, based on this McCabe-Thiele methods and here we take the conditions instead of total condenser we have partial condenser. So, if you recall in our previous discussion, we had when you have the partial condenser, then the top product is withdrawn in the vapor phase and the reflux is sent back to the distillation column as a liquid, so which is in equilibrium with the vapor phase compositions. So, this is the partial condenser; y D, it is not same as x 0 which we had in case of total condenser; in case of total condenser y 1 the composition of the vapor leaving the top plate and arriving at the condenser is same as the composition of the product x D and the composition of the reflux liquid, which goes back to the distillation column.

In case of partial condenser, there is a thermodynamic equilibrium between the top product - vapor product - and the liquid, which is leaving to this; now, the liquid which is going back to the distillation column can also be further sub cooled. So, without saying when we say this partial condenser, we are trying to say that liquid is saturated. We will take another example whether liquid may be further sub cooled below this bubble point.

So, let us take the first example, very small short example, and we confine our discussion only on this partial condenser.

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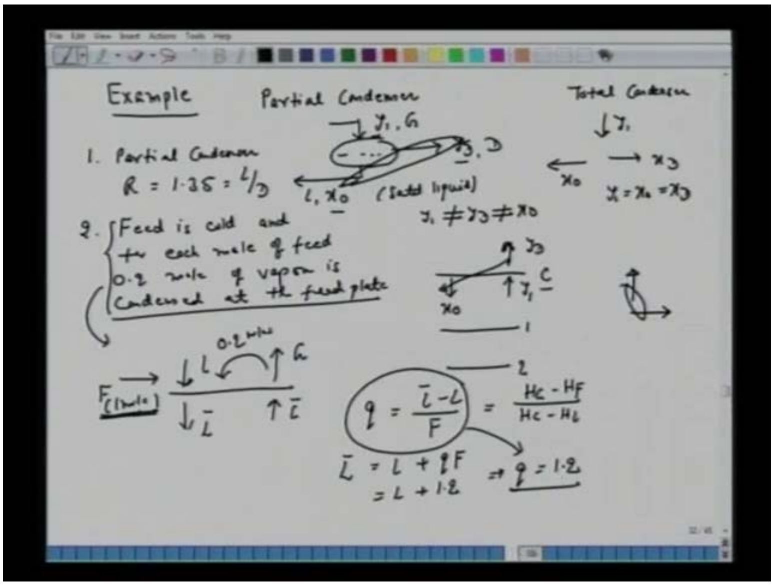

Example

Partial Condenser

Total Condenser

1. Partial Condenser

$R = 1.35 = L/D$

(Satd liquid)

$y_1 \neq y_D \neq x_0$

$y_1 = x_0 = x_D$

2. Feed is cold and for each mole of feed 0.2 mole of vapor is condensed at the feed plate

$$q = \frac{\bar{L} - L}{F} = \frac{H_G - H_F}{H_G - H_L}$$

$\bar{L} = L + qF$

$= L + 1.2$

$\Rightarrow q = 1.2$

So, we take this example of Partial Condenser. So, what we have here is the vapor which comes from the top plate as say mole fraction y 1, molar flow rate is G. So, we have the top product composition say, y D molar flow rate is D, and the liquid, the reflux here, has a molar flow rate of L, and the mole fraction is x 0. So, this problem statement says that, we are using a partial condenser and the reflux is saturated liquid.

So that means, this y D and x 0 is they are in equilibrium. So, compare this to the previous condition of total condenser, where we had composition y 1, the product was xD, and the liquid reflux, this has a mole fraction of x 0, and since it was a total condenser y 1 equals x 0 equals x D, unlike here y 1 is different from y D different from x 0, and the two streams the liquid vapor here, mole fraction y D, is in equilibrium with x 0. So, you must appreciate that this tray or this condenser is acting as a theoretical stage, here we have let us mark this stream. The top product - y D vapor - is in equilibrium with the liquid which is going to this reflux, to this distillation column as a reflux.

So, y D and x 0 they are in equilibrium, and the vapor composition, you know, this stream arriving to this condenser is y 1. So, this is y 1. So, this exactly acting as a theoretical stage, then onward you have first stage, second stage, etcetera. So, this is a condenser which is acting as a theoretical plate, very similar to what we had in case of reboiler, where at the vapor which comes out with the boiler is in equilibrium with the liquid product. So, that is one thing this example, first it says we have the partial condenser, and the description is that this reflux is saturated liquid and the reflux ratio here is given R as 1.35. So, this is L over D.

Now, the problem states that feed is cold. So, feed is cold and for each mole of feed, 0.2 mole of vapor is condensed at the feed plate. So, again try to understand this statement here, before we see how we can solve this problem. So, it says that feed is cold here, if the feed is cold with the flow rate of 1 mole, we have the vapor leaving say at G, we have the liquid arriving here at L, and then underneath this feed plate, the flow rate changes to L bar, and the vapor flow rate in this stripping column is G bar.

So, when the feed is cold, what happens it says that, each mole of feed, per each mole of feed 0.2 moles of vapor condenses. So, this is the basis here, feed flow rate could be something else or it means for 1 mole of feed which arrives here 0.2 moles of vapor condenses. Because, feed is cold, had this been saturated, then you could have 2 situations saturated liquid, saturated vapor, we talked about different values of q which can be assumed, here we have the feed such that 0.2 moles of condenses here.

So, what is the definition for q? Go back to this L bar minus L over F, and of course, from enthalpy balance, you can write H G minus H F over G minus H L. So, look at this expression here, for q in terms of change in this molar flow rate L bar equals L plus qF. Now, if when we have 1 mole of feed enters, 0.2 moles of G condenses, which means L bar is different from L by this 1.2 moles; so if you choose F as 1 mole basis all it means L bar equal to L plus 1.2; F is 1, that means, q as per this definition is 1.2 . So, you should appreciate the statement, and from a very simple, you know, this understanding of the meaning of, this physical meaning of this cold feed, we should be able to calculate this q hence as 1.2.

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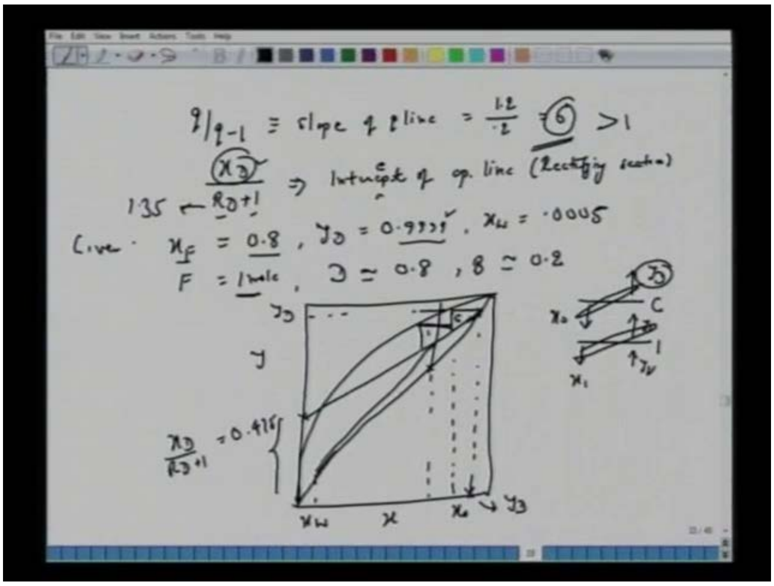

$q/q-1 \equiv$ slope of q line $= \frac{1.2}{.2} = \boxed{6} > 1$

$\frac{x_D}{R_D+1} \Rightarrow$ Intercept of op. line (Rectifying section)

$1.35 \leftarrow R_D+1$

Given · $x_F = 0.8$, $y_D = 0.9999$, $x_W = .0005$

$F = 1$ mole, $D \simeq 0.8$, $B \simeq 0.2$

$\frac{x_D}{R_D+1} = 0.4215$

And then , all it means we have q over q minus 1, the slope of q line equal to 1.2 divided by 0.2 equals 6; that means, the intercept of the operating line for top column or rectifying section is now xD or D plus 1, this is this is your intercept intercept of operating line for rectifying section, top column, top section.

Then, of course, the problem we will say as it reads, you know that simple given xF is a 0.8 mole fractions, y D let us say it is 0.9999 nearly pure in A; bottom product is nearly pure in B, which is 0.0005 mole fraction for A. F is given 1 mole, but mind you, F can be different, still our analysis will be the same, because all we have done, we have chosen F as 1 mole as a basis. So, you can again write your molar balance, species balance to obtain that D you should get approximately 0.8, it is nearly pure A and B should be able to approximately get as 0.2. If you understand this, now we can start, you know construction of these stages, theoretical stages.

So, we have this equilibrium diagram, we have this y versus x; note this q bar over q minus 1 6 greater than 1 or the cold feed. So, if we choose the top product, which is very pure 0.9999 here. Now, let us just try to expand here, may be on enlarge this value is your y D. And we must not forget that we have this condenser here, and then, we have the first stage. So, remember this is y 1 first stage of the top column, and this is x 1; this is y 2; y 1 x 1 is in equilibrium, but condenser is also acting as a stage this y 1, then we have the top product as yD, and the reflux is x 0, and they are in equilibrium.

So, if we know say let us say, feed is 0.8, quite very high large here 0.8, we have the intercept or we have the slope of this q line, which we can draw like this, and we know this XW, it is very small 0.0005 here. So, like this from here, now, if you draw with this intercept xD over R D plus 1; this example, R D was given as reflux ratios, this is given as1.35. So, if you substitute xD 0.8 divided by 2.35, you have a intercept here as 0.425. So, mark this intercept and we shall construction construct this; you have the q line, you can always draw and connect this line, and then we now start making any constructions; first realize that first point, which we use here if you get here, this is y D in equilibrium with x 0, and then, what you get next, that is your first stage.

So, if you go like this, if you go like this here, let us redraw it. Here, if you have connected with this intercept here, like this. So, that is top line, and then, you have this second stage. So, going from this to this, the first stage here is c, that is a condenser, and then, after this you have the first stage.

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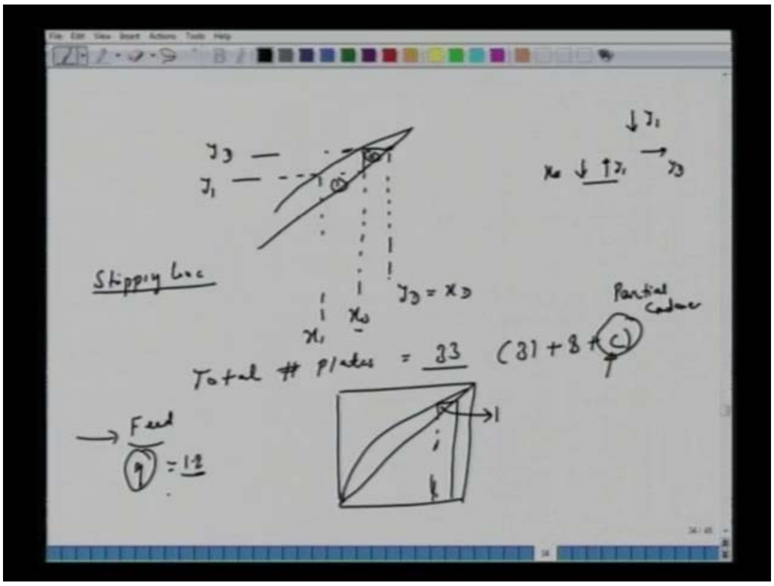

So, let us try to understand if we expand, only the last equilibrium curve, last portion of this equilibrium curve, it is a partial condenser. So, the first stage which will obtain that will be a condenser starting from say yD equal to xD. So, this is 45 degree line here, a top product, you know, it is same yD equal to xD here. So, this is your yD, then what we get in equilibrium will be x 0 reflux. So, the x 0 is the liquid and yD is the top product and what arrives to the condenser is y1.

So, x 0 and y 1, now they would be connected by the operating line, and you will get this as y 1 and then y 1, x 1 they are in equilibrium, so on and so forth, you know, stage C 1, 2, 4 etcetera. You have to proceed, switch to this equation for the stripping line through this q line as an exercise, it must show that you get total number of plates as 33, which will include boiler plus condenser.

So, now we have a condenser - partial condenser - which is acting as a theoretical plate; when you have a total condenser, then in your, what you call in your equilibrium diagram, you start from here, the first itself becomes, first theoretical stage become your first stage, because it a total condenser, so, yD equal to xD come to this; then you have this equilibrium, unlike here where the first theoretical stage will represent condenser like this. So, it is a very simple example on partial partial condenser plus we also talked about the feed which was cold, and from that we got a new values of q as directly as 1.2 from physical understanding, and then we got the slope to draw this line. In this example, we said that reflux is saturated.

Now, we can have one more example, where it is possible that the reflux is below the bubble point; that means, it is a cold. So, similar to the argument we had that the feed could be cold or below the bubble point, it is possible that the reflux is also cold here. In that case, you should realize that when this cold reflux arrives to the top plate, the vapor which is leaving will condense. So, very similar to what argument we had in case of the feed, when the feed was cold, therefore, the when feed enter, at the feed entry, the tray for the feed, then the vapor condensed. So, similarly if the reflux is cold, then the vapor leaving the top plate will also condense, which means the reflux ratios or the amount of the reflux R 0 or L 0 which goes to the column, will now the molar flow rate will change there.

So, it is a very simple calculations, you must realize that there now the reflux ratio will be different or L will be different from L 0. Why? Because the vapor is condensing at the top plate. So, we should be able to calculate actually internal reflux ratios. So, far we had only one, we said that L 0 equal to L; so, we have one reflux ratio. Now you should appreciate that the amount of L 0 is different from L, because some vapor has condensed there. So, we should calculate the new reflux ratios or the apparent reflux ratios R or L by D.

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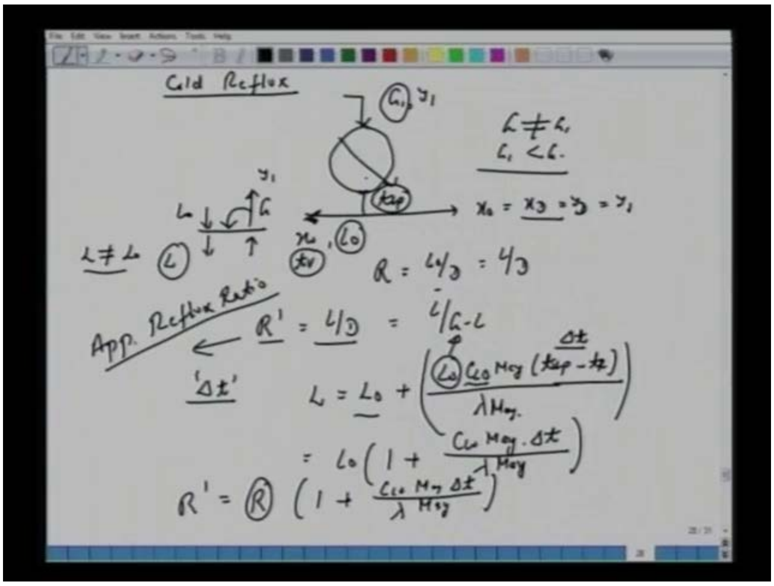

Cold Reflux

$G \neq G_1$

$G_1 < G$

$x_0 = x_D = y_D = y_1$

$L \neq L_0$

$R = L_0/D = L/D$

App. Reflux Ratio

$R' = L/D = L/G-L$

'Δt'

$$L = L_0 + \left(\frac{L_0 C_{L0} M_{avg} (t_{bp} - t_R)}{\lambda M_{avg}}\right)$$

$$= L_0 \left(1 + \frac{C_{L0} M_{avg} . \Delta t}{\lambda M_{avg}}\right)$$

$$R' = R \left(1 + \frac{C_{L0} M_{avg} \Delta t}{\lambda M_{avg}}\right)$$

So, we just make this calculation here, very simple. We have this cold reflux, we have this condenser. So this is G 1, this is y 1, let us say we have the total condenser. So, this is x 0, same as xD, same as y1. So, this is x 0 and this xD and you have this yD, and this yD is same as y1, but now the feed is cold; that means, when it comes to the top plate, then the vapor, which is leaving here, part of this vapor condenses. So, although the composition is y 1 here, but the molar flow rate of this G 1within this column will be different or just G will be different from what we have here in G 1. So, if this amount liquid is L 0, now what we are going to obtain from the first stage onward is L which is different from L 0.

So, L does not equal to L 0; remember we had defined reflux ratio as R equal to L 0 by D or we said equimolar flow rates L by D; now notice that this L is different from L 0. So, we have to calculate the new reflux ratios, R equal to L over D. This L is to be calculated for inside, inside this column not based on L 0, which is same as L over G minus l. So, this notice this is g here different from G 1, G does not equal to G 1, because some the some of the vapor condenses here, that G 1 is smaller than G. So, why we have this condensation? Because this is cold below this boiling temperature, below this bubble point temperatures, so, if this temperature is t r ,then we have and this condenser temperature here is say t d p or the boiling temperature or the bubble point temperature of these fluxes are t d p, and there is a difference of del t which causes this vapor to condense here.

So, what is the quantity? One can write it L equal to L 0 plus the amount which has been condensed, amount of this vapor which has been condensed; now if lambda is the say latent heat of a vaporization L into m average we have L 0 C L 0 m average into t bubble point temperature minus t reflux.

So, this is the sensible heat. So, amount is L 0, it has a specific heat C L 0, some multiplication of this molecular weight to convert the unit from kg to kilomole, and now, we have this del t temperature difference; this sensible heat here is caused, causes results in the condenses of this vapor; notice that if t v p equal to t r or this reflux liquid has reset the bubble point, then we have L equal to L 0.

So, there is a extra amount of the liquid going into this distillation column, which is, you can write as simplify it L 0 1 plus C L 0 m average del t over lambda m average or we can write now, R prime as L by D, as original R based on L 0 by D. So, we have apparent reflux ratios; apparent reflux ratios same as R into 1 plus C L 0 m average del t over lambda m average.

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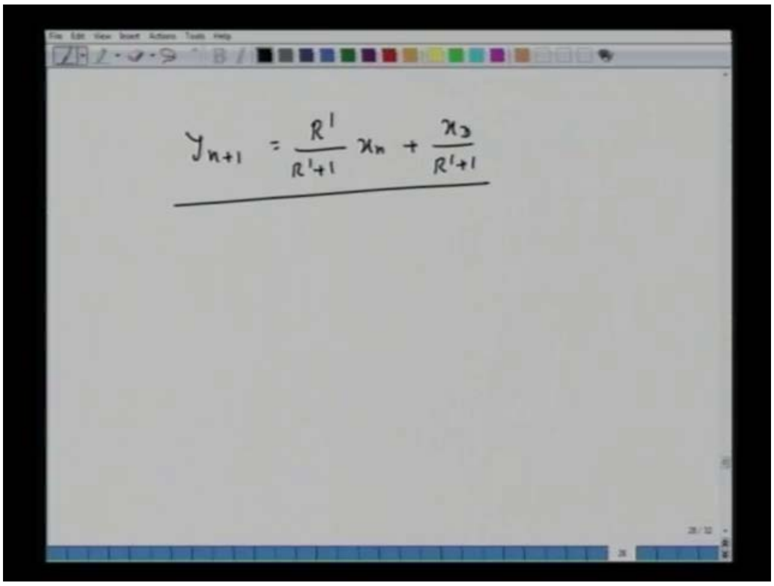

$$y_{n+1} = \frac{R'}{R'+1} x_n + \frac{x_D}{R'+1}$$

In other words, we have the similar operating line for the top column, except now we are going to work on this apparent curve, reflux ratios x n plus xD over R dash plus 1.

So, with this discussion we conclude today’s lecture. We took an example when we had saturated reflux, and then, we had this reflux which was cold. So, in that case we have to work on this apparent reflux ratio.

We also took an example, when we had the total condenser and we had we had this partial condenser. So, difference between total condenser and partial condenser is the same as what we had earlier, when we discussed the Ponchon-Savarit methods, the vapor and the liquid they are in equilibrium, in that case, you have first stage which you will get on this y x diagram will correspond to the reboiler, unlike when you do the total condenser, when the first tray which we get on this geometrical, you know, representation of the trays belongs to the first tray.

So, these are the examples you have to it is recommended that you go through McCabe-Thiele method, take some another examples from the textbook Treybal or from other book separation by Dutta and solve as many as problems. Thank you.