Thermal Operations In Food Process Engineering: Theory And Applications

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Lecture - 59
Distillation (Contd.)

Good morning now we come to finish that Distillation and we have already seen that vapour liquid equilibrium curve is the basis for the separation technique to adopt right. And this is the 59 class on the topic of Distillation and it is being continued right.

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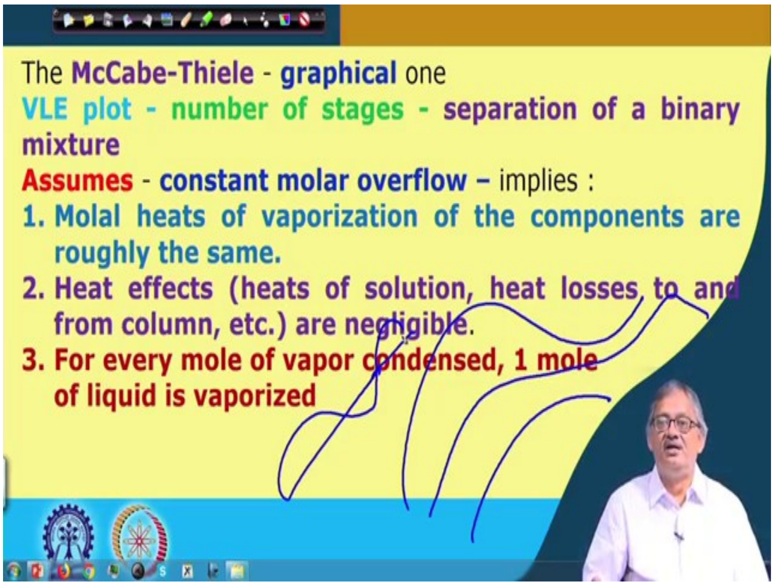

The **McCabe-Thiele** - **graphical** one

VLE plot - number of stages - separation of a binary mixture

Assumes - **constant molar overflow** – implies :

1. **Molal heats of vaporization of the components are roughly the same.**
2. **Heat effects (heats of solution, heat losses to and from column, etc.) are negligible.**
3. **For every mole of vapor condensed, 1 mole of liquid is vaporized**

And if we remember, that where we finished in the last class we had said that the vapor liquid equilibrium curve is the basis for the separation of the and where the curve nature of the curve right. So, this was one nature or this was another nature or this was another nature right as well we had seen with the diagonal this intersection of the vapour liquid equilibrium curve was there for isotrope. So, from the nature of the curve you can understand how good the separation will take place or how easy it can be done.

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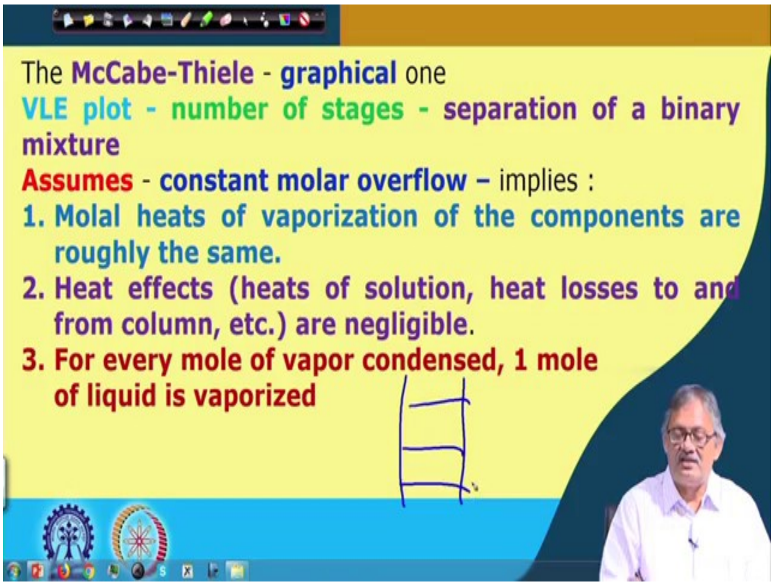

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So, to do that to make the design of the column there we have already said trays and other things all these. We have said boiling point diagram also from there we are getting this vapour liquid equilibrium curve right. And this we can say that by the method called McCabe-Thiele graphical method we can easily determine; how many number of trays or how many segments are required for the interaction of the vapour liquid.

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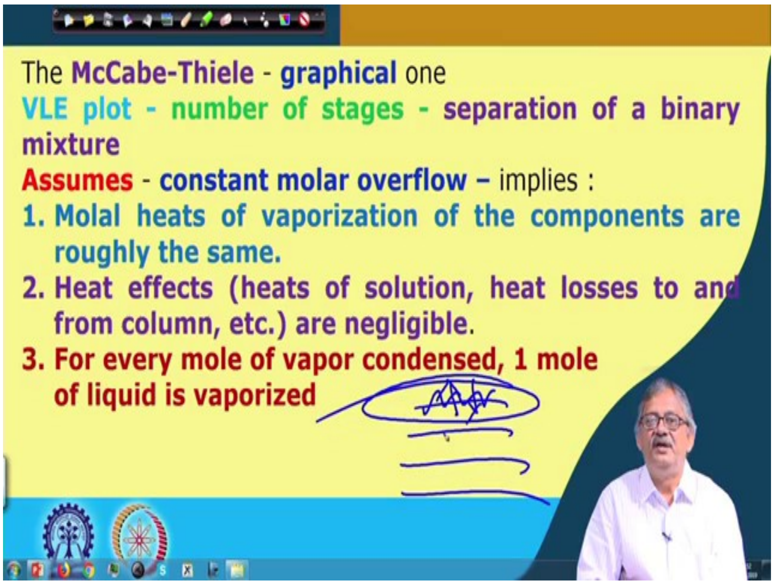

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Earlier he said each tray is acting like a mini column because, in each tray the same thing is happening that vapour is going up liquid is coming down. There is a exchange of heat exchange of mass both and there by separation is taking place right. So, here with the McCabe Thiele graphical method from the VLE plot we can determine the number of stages required and the separation of a binary mixture is feasible to do or feasible to work out right.

Obviously some assumptions are also associated, you can assume that constant molar overflow right. There is a first assumption is that there is a constant over constant molar overflow at the constant molar overflow, means that molar heats of vaporization of the components are roughly the same. Molar heats of vaporization of the two components are same roughly number 1, then heat effects that is heats of solution or heat loss to and from the column etcetera that is negligible right.

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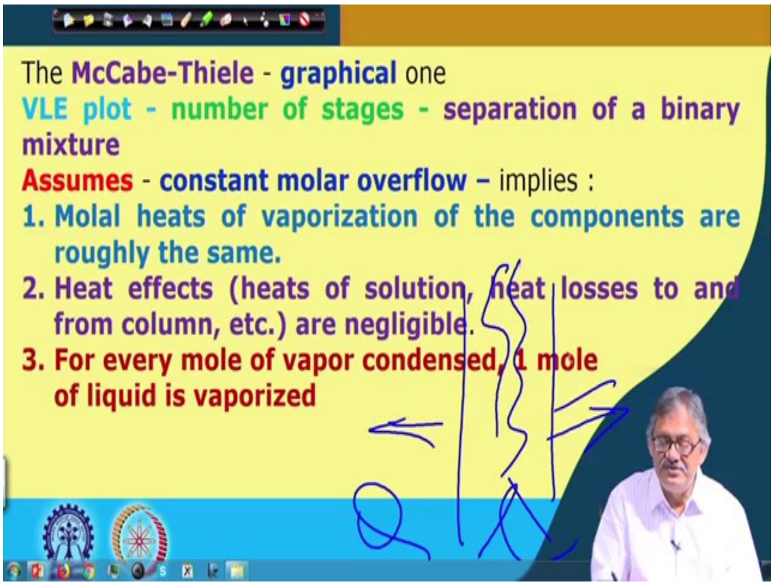

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Because, if you are giving from the reboiler, some heat Q to the liquid there by the vapour and before it is coming in contact with the liquid. If lot of heat is being dissipated through the column then you are losing lot of energy, so that is not being accounted for.

So, assumption is that heat effects that is heat of solution and in many cases heat of solution can be endothermic or exothermic right. Since, it has come and I am just saying heat of solution can be exothermic or can be endothermic.

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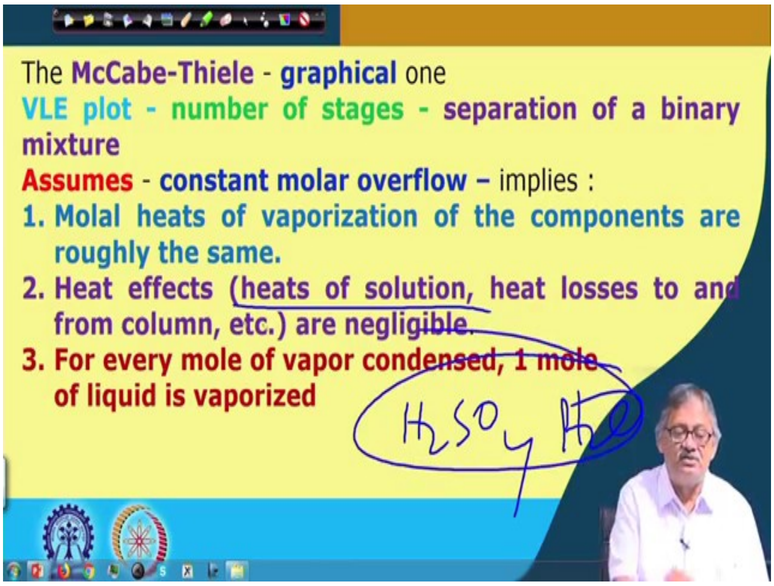

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H_2SO_4 H

Example that you have done with sulphuric acid H_2SO_4 you have put if we put water add to that and if you are holding that test tube you and acid and put the water you cannot hold that test tube for a long time, because it becomes very very exothermic highly right. So, that is exothermic, so that heat of solution we are neglecting. Similarly the reverse endothermic you know ammonium chloride you put in water and you will see that your test tube has become cold, so that is called endothermic.

So, it is neither endothermic nor exothermic heat of solution heat lost from the or to the heat lost or gained to and from the column is also negligible that is the second assumption and third is for every mole of vapour consists a condensed 1 mole of liquid is vaporized right. So, if 1 mole of vapour is condensed then 1 mole of liquid is vaporized that is also that is why it is being said that constant molar overflow. That if every mole of liquid is vaporized, so 1 mole of vapor is separated or condensed right, so this is the assumption on which the entire this graphical method is resting on.

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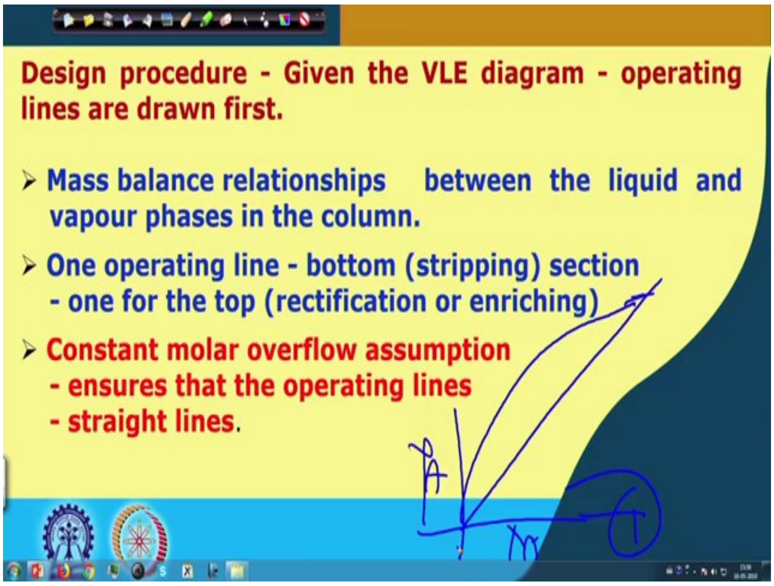

Design procedure - Given the VLE diagram - operating lines are drawn first.

- Mass balance relationships between the liquid and vapour phases in the column.
- One operating line - bottom (stripping) section
  - one for the top (rectification or enriching)
- Constant molar overflow assumption
  - ensures that the operating lines
  - straight lines.

So, design procedure is that first you know that Rayleigh diagram that is vapour liquid a liquid diagram. So, from there you draw that vapour liquid diagram we will show you afterwards in a bit better one. So, you have this is Y this is X, so you have that vapour liquid diagram right and you have this operating line and this is not the operating line this is the diagonal.

So, you know what is what are the things you need to know? You need to know at what fraction mole fraction your liquid is coming in right. At what mole fraction your liquid is coming in or at what mole fraction your vapour is going out or at what mole fraction your feed is coming in right. So, these are the some of the things which are known right or predetermined right, then only you can you this you know the starting point, you know the end point and also you know where the feed is being done right.

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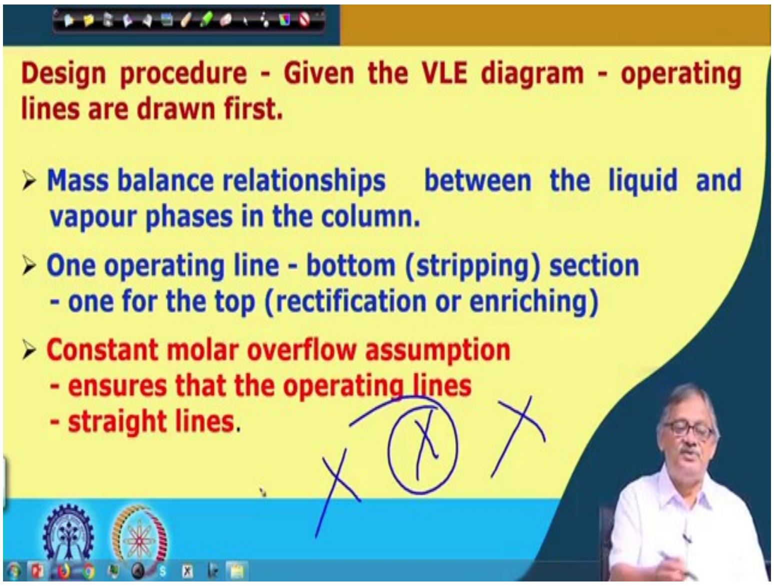

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So, this entire thing is dependent on the mass balance relations right between the liquid and the vapour phases in the column right. Mass as well as heat balance one operating line or bottom stripping section and one for the top that is called rectification or enriching section are known or you have to construct right. And, then constant molar overflow assumption is also we have taken earlier and that ensures the operating lines right.

And the operating lines become straight, because it is under constant molar overflow that is why operating lines if they would have been like this or curvilinear it will be very difficult or clumsy. So, that is why if this assumption is very valid that the operating line which you will see now is straight or to make it straighten you have assumed that this is to be constant molar overflow ok.

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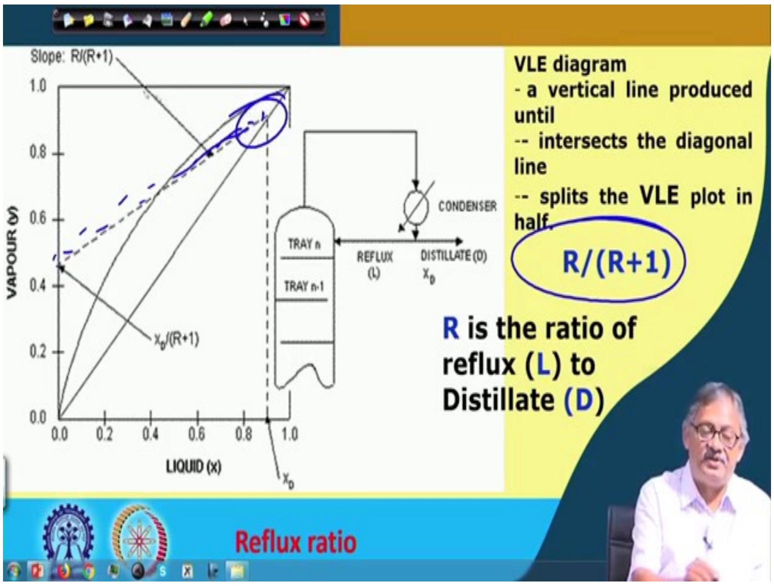

VLE diagram
- a vertical line produced until
-- intersects the diagonal line
-- splits the VLE plot in half.

R/(R+1)

R is the ratio of reflux (L) to Distillate (D)

Reflux ratio

That means, what you said if 1 mole of liquid is vaporizing then 1 mole of vapour is also condensing to liquid ok. Then from this you see what we can say that this is a vapour liquid diagram that is this line right. So, a vertical line is produced until it intersects ok, from there what you do is that you know that what is the liquid concentration liquid as a 0.8 right mole fraction. So, you are you are starting with that 0.8 mole fraction. So, make a vertical line like this which is intersecting with the diagonal at this point right and this leads the vapour liquid equilibrium line into two hubs one is the rectification and a another is the or stripping right.

So, this is these are the two which are associated with this right and as we see from here that that part of it is refluxed right. So if you look at the other part, so this is one diagram right another diagram is this side, that if you see that we have taken this tray l portion right this is the n^th^ and (n – 1) maybe after this is (n + 1) tray right. This is a condenser and from the condenser part is taken off as the distillate, so you know what is the mole fraction of the distillate and a part of liquid is refluxed as L right.

So, the reflux ratio r is nothing, but r / (r+1) where r is the ratio of reflux of L or liquid to the distillate right that is which is coming out as D right. So, this is the liquid mixture and this is the distillate which has come out with that mole fraction which you want right and you have made this vertical line which is intersecting here at this point and now with a slope of R / (R+1).

This is the slope with the slope of R / (R+1) you had made this line operating line right, operating line of the enriching section that upper half is called enriching section and bottom half we said it is the stripping section. So, in the enriching section with this R / (R+1) we have made this operating line right. So, once we know that then and also we know the reflux ratio that is R right, the slope is R / (R+1) ok. Which tells that how much part is refluxed and how much part is going out as the distillate right, so from there distillate means which is the output.

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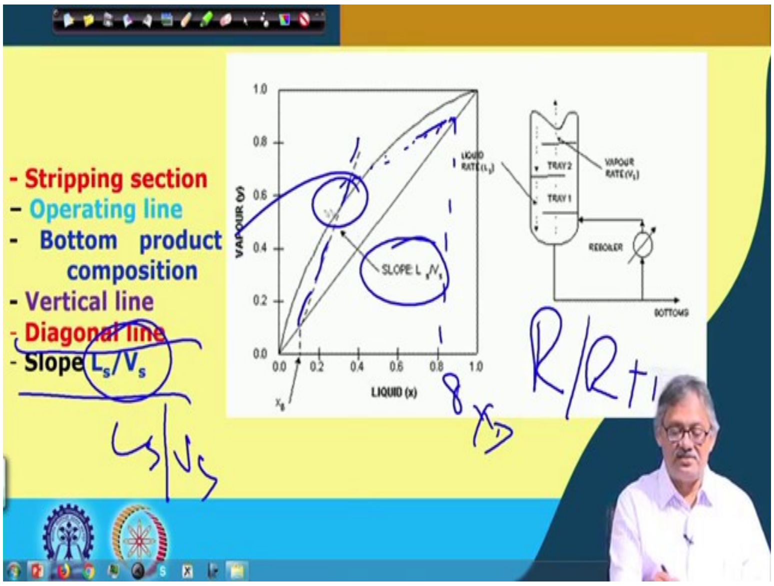

- Stripping section
- Operating line
- Bottom product composition
- Vertical line
- Diagonal line
- Slope L_s/V_s

From there we can now say that this is again that the stripping section line again this is that reboiler right and we are this is bottom coming out and the vapor is being fed through the reboiler and vapours are going over and liquid is coming from there. So, vapour rate is V_s right and in this stripping section the operating line we have to find out which is the bottom product composition right. Bottom product composition is X_B right. So, if we know that bottom product composition here.

So, we go vertical to that which is intersecting with the diagonal that is the beginning right, from where we do the diagonal line with there as a slope that is L_s / V_s. So, the slope is here L_s / V_s right and we can this L_s / V_s from there this slope we can draw this operating line which is intersecting with the equilibrium line here. And if you remember earlier we had taken just their 0.8 as the X_D right and this vertical with a with a slope of

(R+R) / (R+1). We had made this that is the operating line for the enriching section and this is the operating line for the stripping section.

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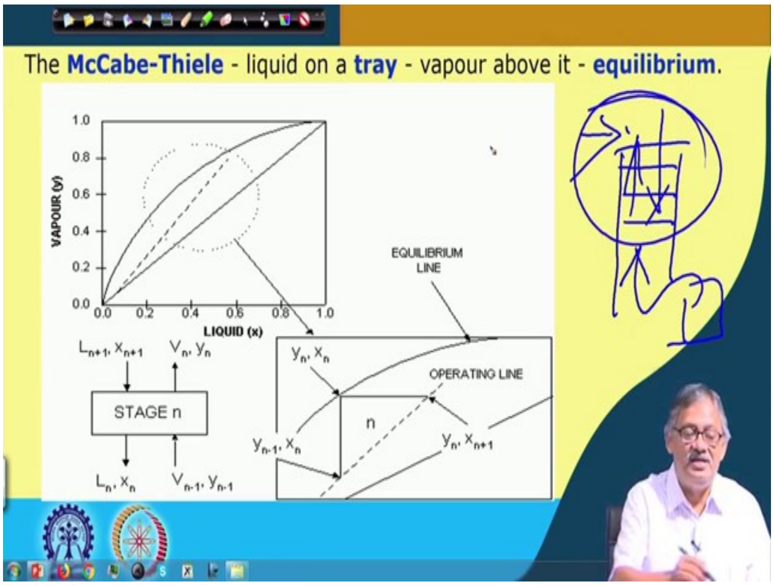

The **McCabe-Thiele** - liquid on a **tray** - vapour above it - **equilibrium**.

So, once we have both the operating lines for enriching section sorry and stripping section, we can say that this is what is for the nth tray we are not now considering earlier we had shown if it would have been column, if reboiler would have given from there right reboiler has given it vapour and this is going like this and the liquid is coming like that from the feed right. Feed was made like that till now we have not told where the feed is being made right. But we are saying that they are interacting with the different trays.

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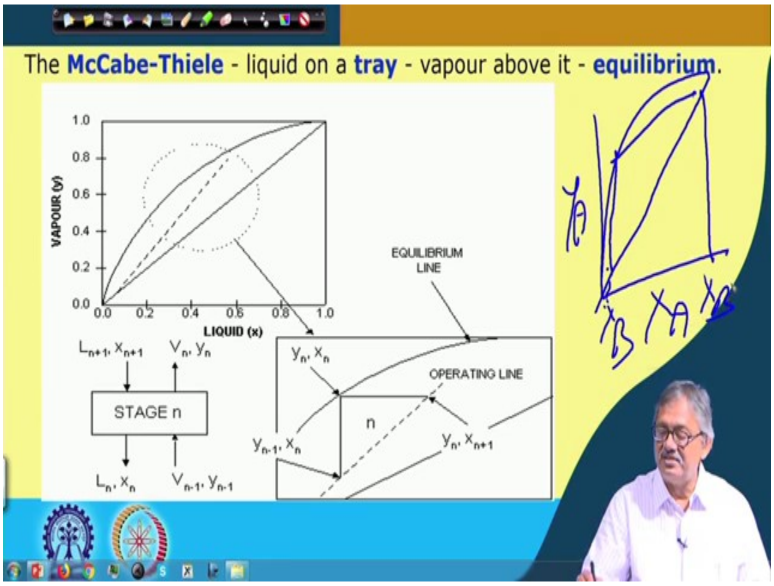

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And, we could have by this time we could have made that X_A and Y_A we could have made that vapour liquid equilibrium line and d and with this diagonal of 45° line from there this was our output right. And, R / (R+1) we have made this operating line for the enriching section and we also have made this for the stripping section where it is X_B and where it is X_D right. So, this much we have done now in between the column.

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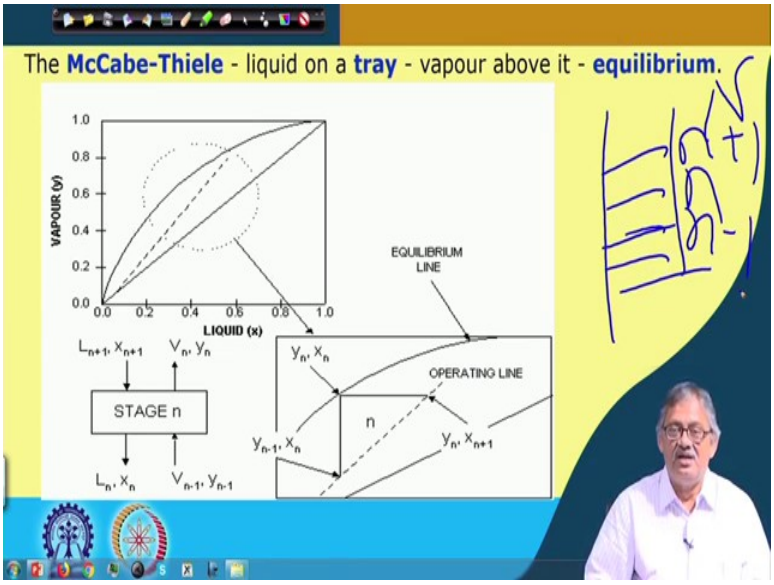

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So, we have we do not know how many trays are there. So, there could be capital N number of trays out of which say small nth tray this is $(n+1)^{th}$ tray, this is $(n-1)^{th}$ tray we let us look at those trays right and that is what we have given here right.

So, if we that what is actually happening that in the stage nth or nth tray the vapours which are coming they are $(L_n + 1)$ X_n from l (n+1) and (X_n+1) liquid and vapor is going out from this as V_n and Y_n. Whereas, the liquid which is coming out from here is L_n and X_n and the vapour which is going in is the (V_n-1) and (y_n-1) from the previous tray (n-1) and it is also from the after tray there is (n +1) right.

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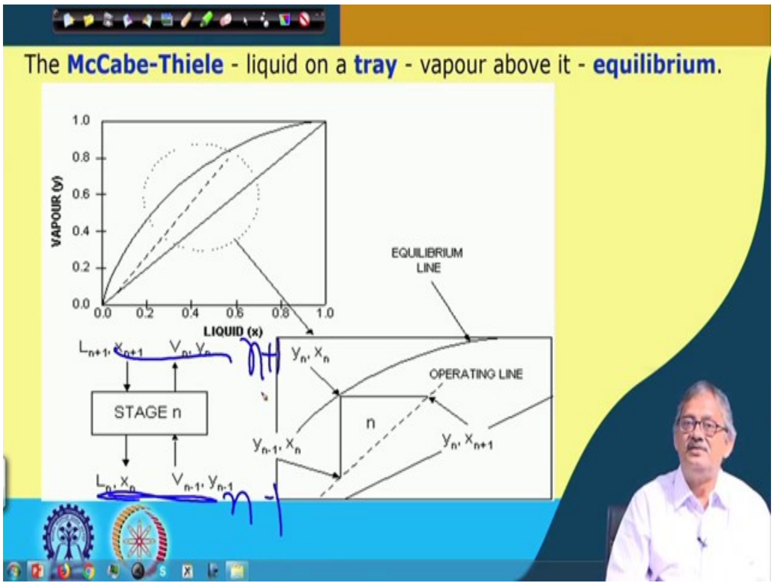

The **McCabe-Thiele** - liquid on a **tray** - vapour above it - **equilibrium**.

This is exactly we have made this for this picture that we have this equilibrium line right, we have operating line right and this is the nth right. So, this corresponds to (n-1) or (y_n-1) x_n at this point this point $y_n \times (x_n+1)$ right. And, this point is y_n x_n right and if we then look at the entire thing.

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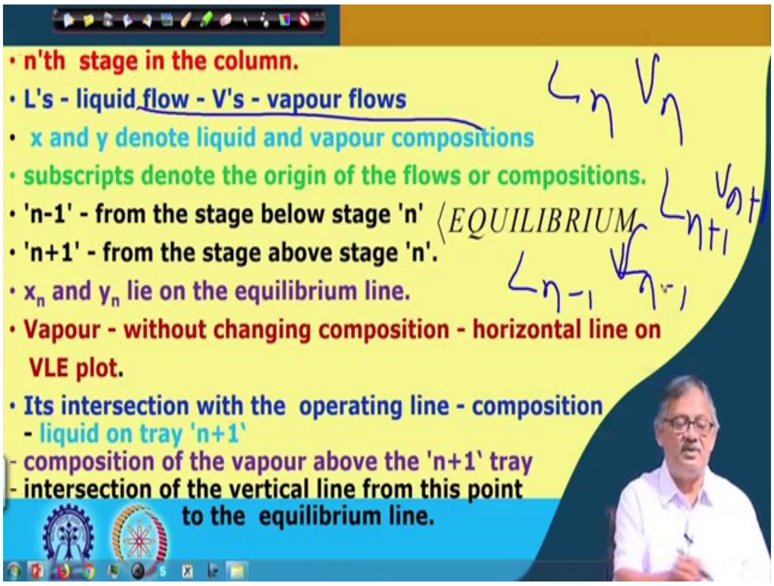

- n'th stage in the column.
- L's - liquid flow - V's - vapour flows
- x and y denote liquid and vapour compositions
- subscripts denote the origin of the flows or compositions.
- 'n-1' - from the stage below stage 'n' ⟨EQUILIBRIUM
- 'n+1' - from the stage above stage 'n'.
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- Vapour - without changing composition - horizontal line on VLE plot.
- Its intersection with the operating line - composition
  - liquid on tray 'n+1'
- composition of the vapour above the 'n+1' tray
- intersection of the vertical line from this point to the equilibrium line.

L_n V_n

L_{n+1} V_{n+1}

L_{n-1} V_{n-1}

Then we see that the nth stage is in the column we are looking at and L_s are liquid flow and V_s are vapour flows for all the trays right; so, whether it is L_n V_n or $(L_n + 1)$ (V_n+1) or $(L_n – 1)$ V_l sorry $(V_n – 1)$. Whatever v all L_s and V_s are liquids and reverse right and X and Y did all the liquid and vapour components that is the mole fraction this component is called in terms of mole fraction right.

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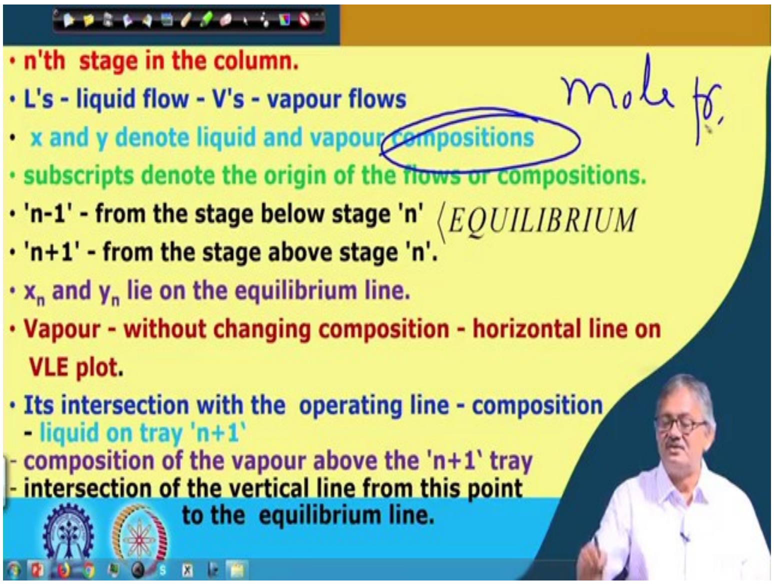

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mole fr.

So, that mole fraction you know and then subscripts denote the origin of the flows or the components where from it has started.

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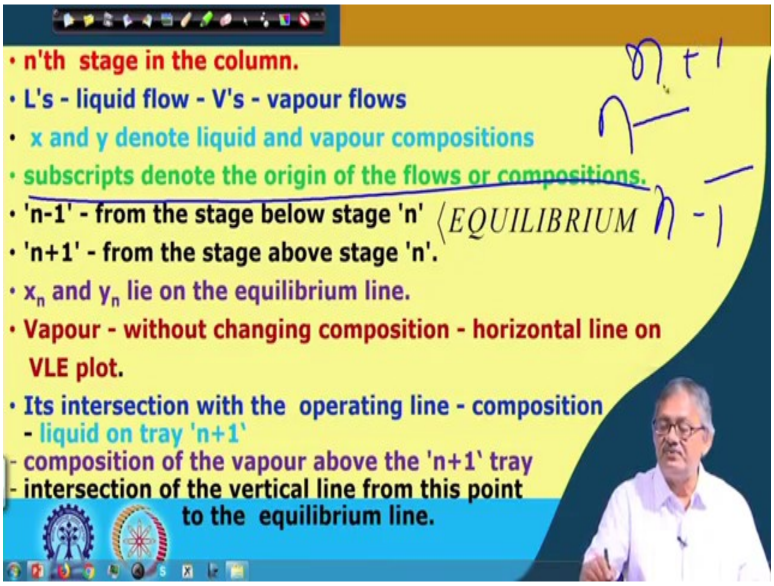

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If it is from n if it is n then from the nth stage, if it is (n – 1) then from the $(n-1)^{th}$ stage. If it is (n+1) then from the $(n+1)^{th}$ stage right. So, (n – 1) from the stage below the stage n and (n+1) from the stage above the stage n, where both are in equilibrium with the n right, (n+1) is also in equilibrium with n and n minus is also equilibrium with n.

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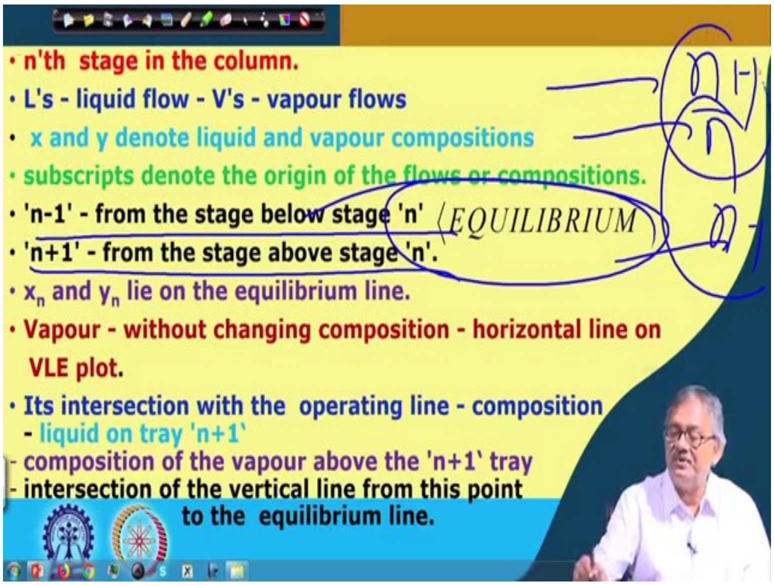

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So, both this so this and that this is a n^{th} this is $(n+1)^{th}$ and this is $(n-1)^{th}$. So, these are in equilibrium right. So, once we know that X_n and Y_n lie on the equilibrium line, where vapour without changing composition horizontal line on the VLE plot. And its intersection with the operating line that is the composition of the liquid on the tray (n+1). Composition of the vapor above the (n+1)th tray is also there and intersection of the vertical line from this point to the equilibrium line that we get as the where is the composition in the nth + 1 or nth tray right.

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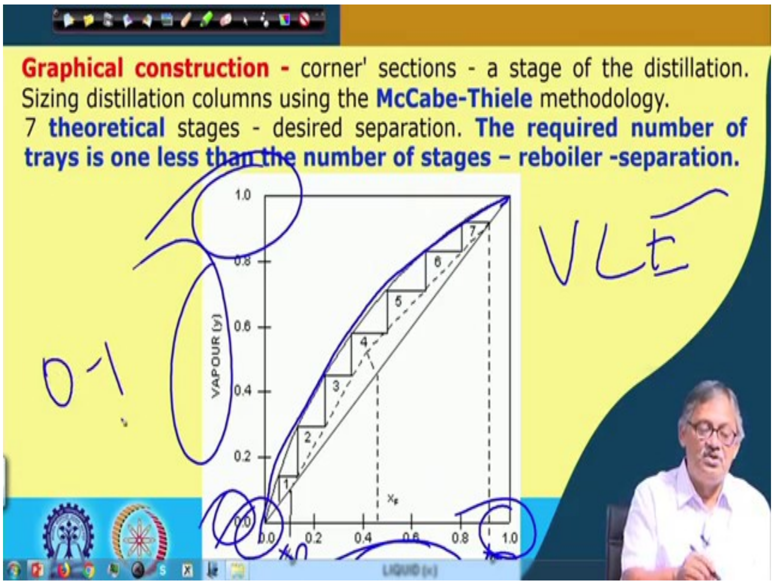

Graphical construction - corner' sections - a stage of the distillation. Sizing distillation columns using the **McCabe-Thiele** methodology. 7 **theoretical** stages - desired separation. **The required number of trays is one less than the number of stages – reboiler -separation.**

Now, if we look at the overall then comes like this, that graphical construction we can say that this typical drawing we have made for 7 number of stages or theoretical stages right. By the McCabe Thiele method we have plotted this VLE or vapour liquid equilibrium line right and we have come to know what is the XD we have come to know what is the XB right.

There is a mole fraction this is the mole fraction of our vapour composition this is the liquid composition in terms of mole fraction. You see both are varying between 0 to 1 because it is mole fraction which varies between 0 to 1 right.

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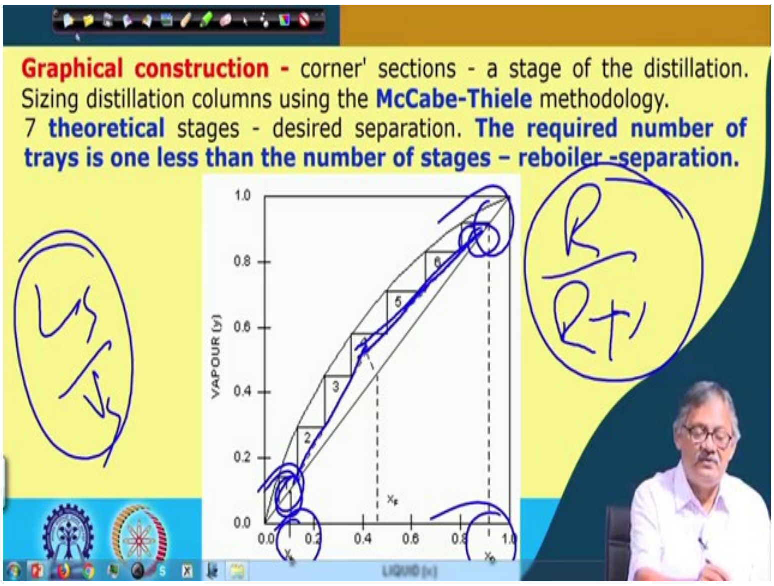

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And we have come across that what is the end point that is X_D distillate mole fraction is so much and what is the mole fraction from where we started that is X_B that is boiling right boiler or reboiler right. And we have found out from this point what is reflux and what is reflux ratio right.

And from there R / (R+1) this slope we have plotted this and then from this point we have plotted L_s / V_s that is that liquid right. We have seen what is the slope of this line accordingly we have drawn it right and then we also know another thing which is called feed or what is the feed condition.

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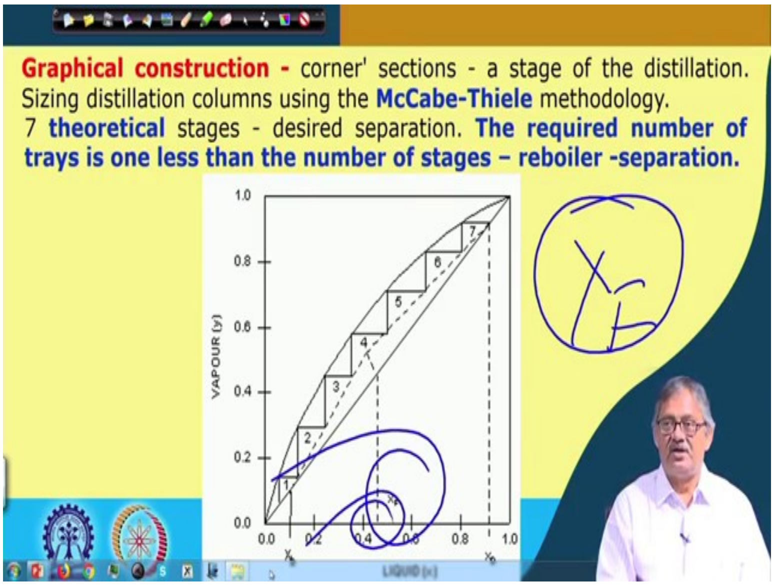

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So, corresponding composition at the feed except that we have plotted we have drawn and from there a vertical line on the on the diagonal is the beginning and from there this q line we have drawn and this is called q line or feed line right this is called q line or feed line right which will come afterwards maybe a little bit more.

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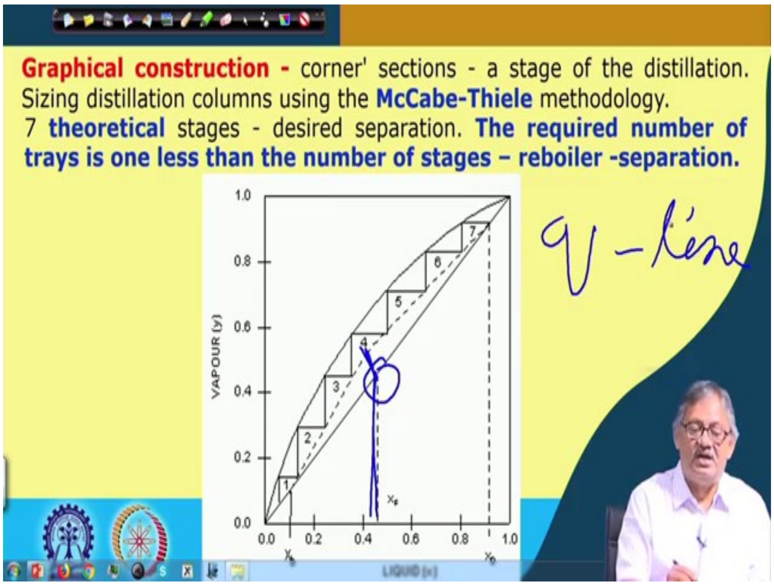

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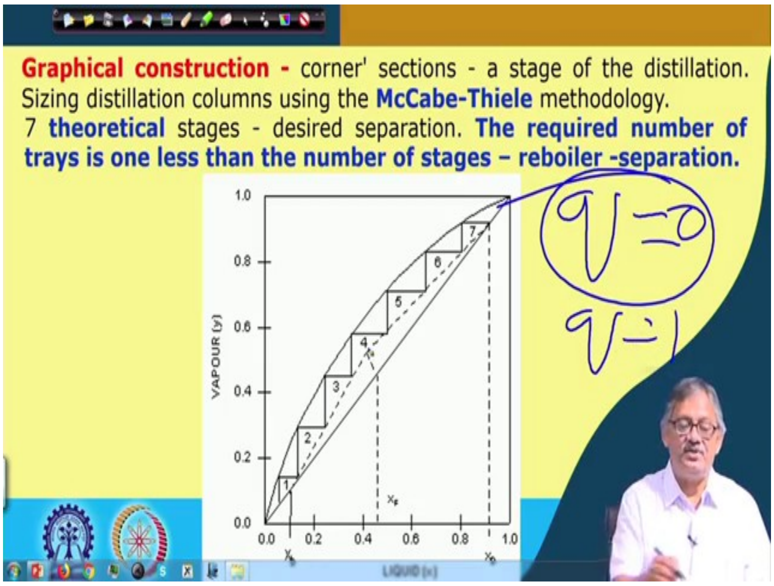

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Because depending on what is the q value whether the q=0, q =1, q > 1, q <1 all these will dictate the nature of this q, where it will meet with the intersection. So, the in normally once you get it and once you have this operating line two operating lines intersecting that point is joined with the with the feed composition in the in the diagonal and that is the q line and that tells where actually the feed tray should be resting on right. So, we have seen that with this method of McCabe Thiele, we have proceeded found that number of stages required are 7.

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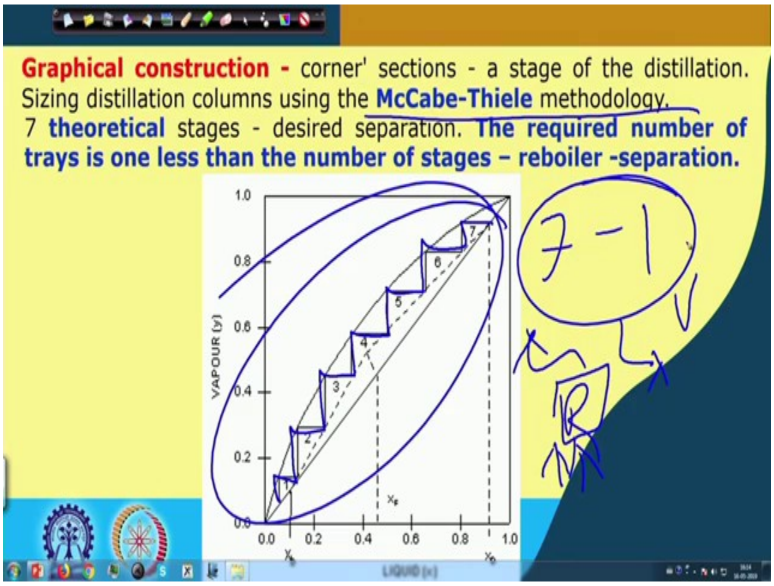

Graphical construction - corner' sections - a stage of the distillation. Sizing distillation columns using the **McCabe-Thiele** methodology. 7 **theoretical** stages - desired separation. **The required number of trays is one less than the number of stages – reboiler -separation.**

But actually it will be (7-1) the reason being we had originally that reboiler right. So, that reboiler is also acting as a separation stage because, you were heating in the reboiler that is also a heat exchanger. You are heating with the steam or whatever heating medium and there you are separating both the liquid component at the vapour component, so that you are using as the separation unit right. So, once you know that then you are very much sure that this reboiler is also acting as one of the stage.

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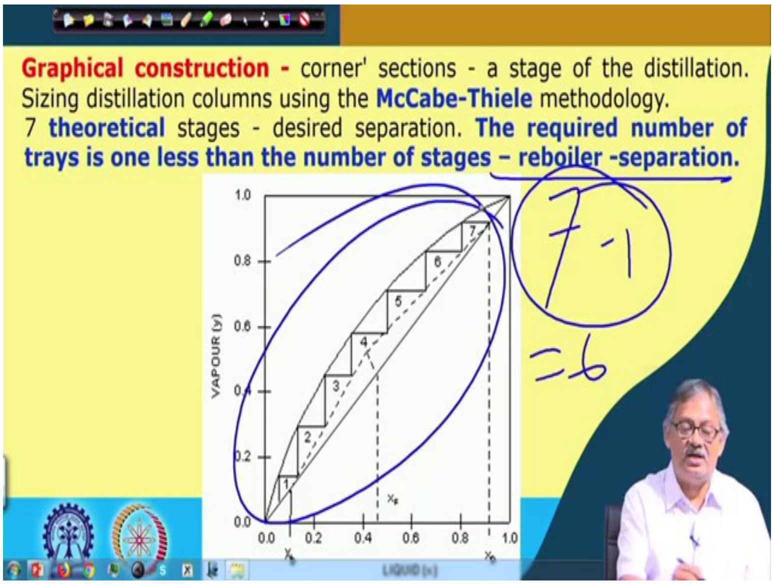

Graphical construction - corner' sections - a stage of the distillation. Sizing distillation columns using the **McCabe-Thiele** methodology. 7 **theoretical** stages - desired separation. **The required number of trays is one less than the number of stages – reboiler -separation.**

7-1

=6

So, if by the graphical method you get 7 number of stages, then actual stage required is (7-1) is 6 because reboiler is also acting as a separation separating stage right.

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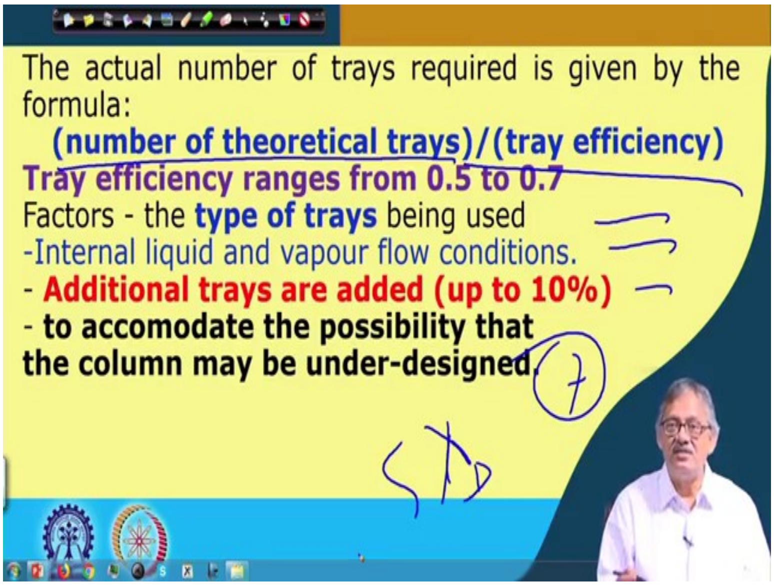

The actual number of trays required is given by the formula:

(number of theoretical trays)/(tray efficiency)

Tray efficiency ranges from 0.5 to 0.7

Factors - the **type of trays** being used

-Internal liquid and vapour flow conditions.

- **Additional trays are added (up to 10%)**

- **to accomodate the possibility that the column may be under-designed**

So, we were talking about q line right, the actual number trays is given by the formula like this which we have just said number of theoretical trays over tray efficiency. Normally efficiency is also a factor, because it may be that you have drawn 7 trays are required. But efficiency is low. So, X_D you need, but it is not coming it is coming less than X_D because tray efficiency you have not considered.

So, if you consider tray efficiency normally it varies between 0.5 to 0.7. So, that will give you how many number of trays you need, if it is the additional trays then up to 10% you may add. But to accommodate the possibility that the column may be under designed. See if the column is under design then you need the rather your rectification or your separation will be less, so that is why a little more around 10% or even more extra is given.

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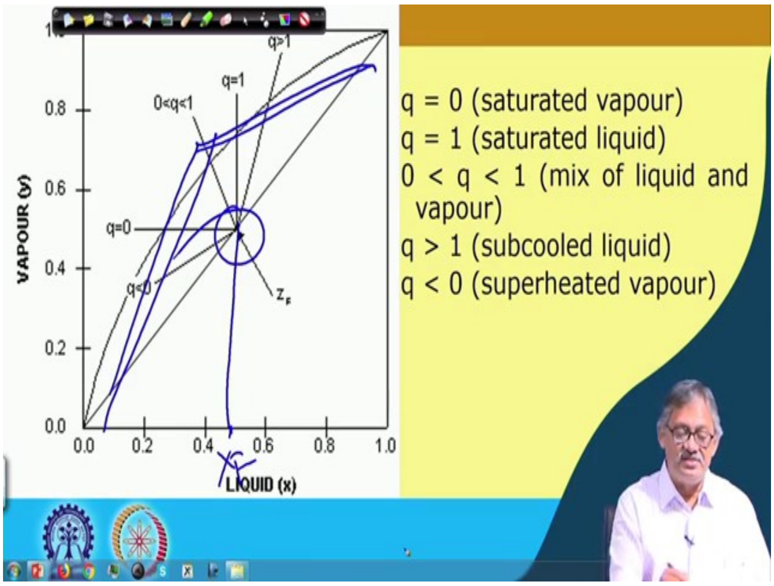

q = 0 (saturated vapour)
q = 1 (saturated liquid)
0 < q < 1 (mix of liquid and vapour)
q > 1 (subcooled liquid)
q < 0 (superheated vapour)

Now a vital thing which you are talking about was this that the q line that is the feed line right. So, feed is intersecting here we said here that was the X_F sorry that was the X_F right this point was X_F feed composition. So, from there the vertical point it is intersecting here.

So, it can be that because we do not know what is the q slope right, we have we know that what is the slope for enriching section, we know what is the slope for the stripping section, so we could easily draw. But what is the slope for q line that is not said. So, normally it is that if q = 0, that means saturated vapour that means q line will be dictated by what is the feed condition.

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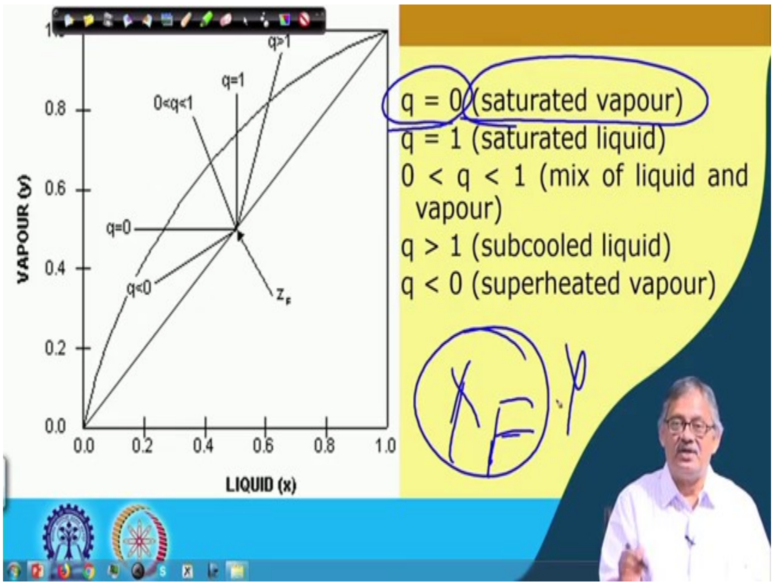

q = 0 (saturated vapour)
q = 1 (saturated liquid)
0 < q < 1 (mix of liquid and vapour)
q > 1 (subcooled liquid)
q < 0 (superheated vapour)

So, you will be said that feed is at this temperature or at the boiling point or whatever it will be said. So, q=0 corresponds to saturated vapour, q =1 is corresponds to saturated liquid right. So, both at the phase at the same temperature, but the different phase in equilibrium as, that is the temperature curve. At which in the becoming equilibrium right or boiling or condensing temperature, q can be between 0 to 1 where mix of liquid air vapours are there. So, you have both liquid vapour together as the feed or you can be q>1 so there means it is a sub cooled.

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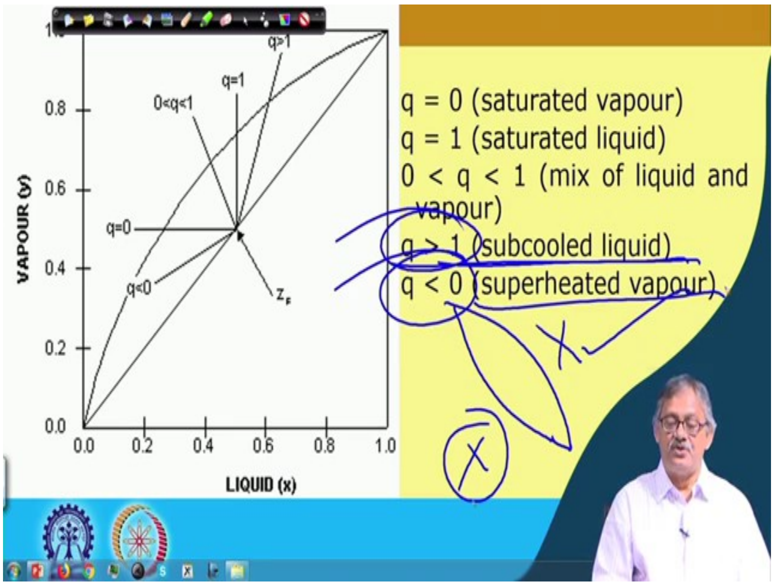

q = 0 (saturated vapour)
q = 1 (saturated liquid)
0 < q < 1 (mix of liquid and vapour)
q > 1 (subcooled liquid)
q < 0 (superheated vapour)

If you remember in that boiling point diagram we had said this is the superheated region and this is the sub cooled region. So, that is the sub cooled liquid and if $q < 0$ then it is superheated vapour. So, the how you are defined with that feed condition that will tell whether sleep is $q > 1 = 1$ between 0 to $1 = 0$ or < 0. Accordingly your this slope will be decided and you can find out the q line right. So, once you have determined that what is the feed point feed line then you have determined the entire number of this.

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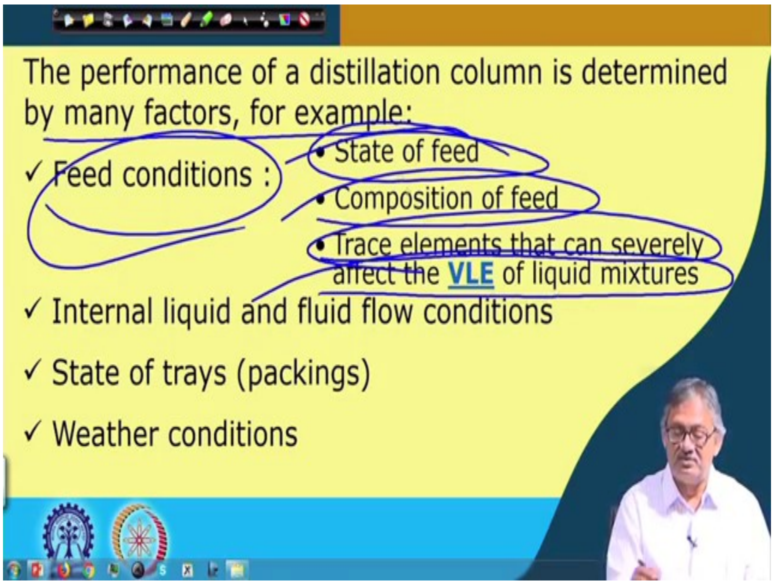

The performance of a distillation column is determined by many factors, for example:

- ✓ Feed conditions :
  - State of feed
  - Composition of feed
  - Trace elements that can severely affect the **VLE** of liquid mixtures
- ✓ Internal liquid and fluid flow conditions
- ✓ State of trays (packings)
- ✓ Weather conditions

So, the purpose of a distillation column is determined by the many factors, for example feed conditions. Whether the state of the feed were at what state it the feed is being made composition of the feed, then trays elements that can severely affect the VLE that is vapour liquid compositions right. Vapour liquid composition of the mixtures if there are trays elements as the your as one of the rather.

If the there are stress element has one of being what we say that it has become I mean that trays element. If that is present as the external material or internal liquid and fluid flow conditions and state of the trays weather packing or what is the weather condition all will dictate how the performance of the column or distillation tower will be there right. So, with this we have come to the end of this distillation and hopefully you could make it and you can now draw and find out from one to other and this is a graphical method. So, it takes time and you can do it at home also ok.

Thank you.