Lecture – 30
Continuous multistate fractionation

Welcome to the 5th lecture of module 5 of Mass Transfer Operation and in this module we are discussing distillation mass transfer. So, before going to this lecture let us have small recap on our previous lecture. In our previous lecture we have mainly consider two important things. One is batch distillation.

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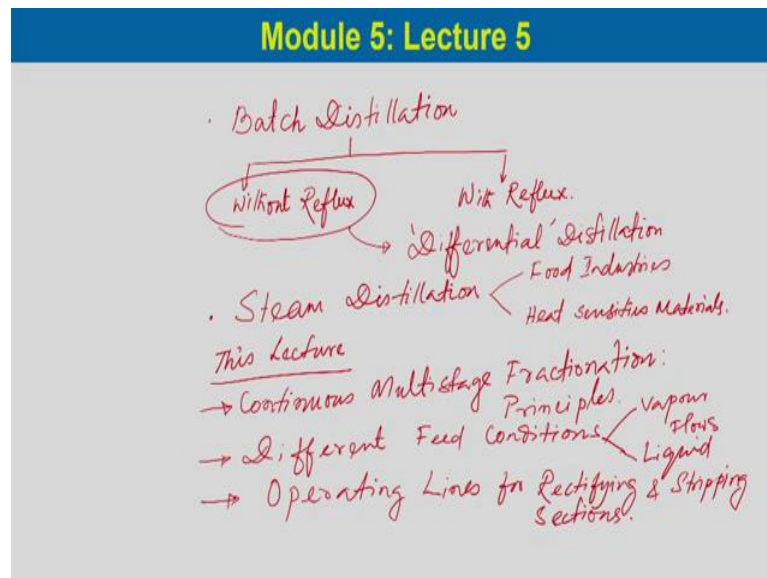
Under batch distillation we have there are two variants as we have discussed, one is without reflux and another one is with reflux. So, we have considered in our previous lecture only this part that is batch distillation without reflux and which is also termed as differential distillation. And this batch distillation has huge applications as we have discussed and we have sought for you know how to calculate the different composition in case of batch distillation. And the second thing we have considered is you know steam distillation and we have seen that steam distillation has you know major application in food industries and for the separation of heat sensitive materials.

In this lecture we will mainly consider the continuous multistage fractionation its principle, and the second thing we will consider that different feed conditions and based

on the feed conditions how this feed conditions changes flows of the vapour and liquid in the column internals. So, how this feed condition changes the vapour flows and liquid flows inside the column that we will discuss. And finally, we will you know obtain the operating lines for you know rectifying and stripping section. So, mainly these three things we will systematically discuss in this lecture.

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So, this is a typical as you have seen earlier, typical tray multistage distillation column. Fractional distillation or fractionation is normally used to separate liquid mixture into two or more vapour or liquid products with different compositions. So, this is a complete fractionation as shown over here, you can separate two or more components and either it is you can get the product as a vapour form or you can get as a liquid forms.
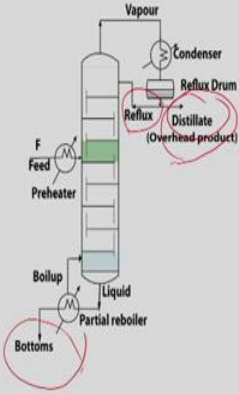
So, with different compositions as you want from the different tray locations it is an equilibrium stage of operation and in each stage a vapour phase is contacted with a liquid phase. So, you can see there are number of trays and each trays the vapour and liquid are come in intimate contact and they reach equilibrium and then they move from one tray to the other.

So, the less volatile that is called know heavy components or the high boiling components they concentrate in the liquid phase. So, the less volatile component will concentrate on the liquid phase or in the liquid phase.
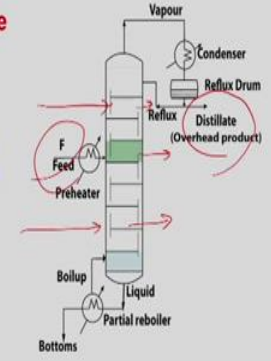
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And the more volatile component which is called light component they concentrate on the vapour phase. So, by using multiple stages in series with recycle and separation can be achieved. So, you can see multiple stages shown over here and part of the product, suppose if you have a distillate taken out from the overhead product and part is returned over here. So, no the degrees of separation you want to get you can obtain from here and as we said the less volatile component we will concentrate on the liquid phase. So, less volatile component will be richer in the bottom product because the liquid will fall down and you can get a liquid product over here and then vapour the lighter components more volatile components will move upward and you will get the more volatile component as a distillate product at the top.
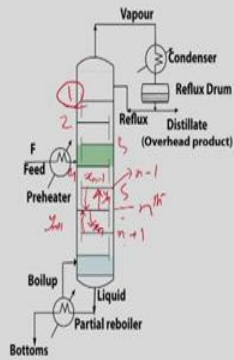
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The feed to the to a distillation column maybe liquid, vapour or a liquid vapour mixture. So, any kind of feed you can use over here, either it is a liquid or it is a vapour or it may be a vapour liquid mixture. So, either of these three combination we can use as a feed to the column. It may enter at any point in the column although the option optimal feed tray location should be determined and used. So, you can feed at any tray from the top to bottom as a you know feed entry, but which for the optimal operation. So, that you need to find out with a proper procedure what would be the feed tray location to get optimal output from this?

So, that we will discuss in the later stage of our discussion the remaining lectures. So, more than one stream may be fed to the system and more than one product may be drawn. So, instead of a single feed you can have multiple feed tray into the column and also the product instead of taking product at a top you can have different stage cart at different location. So, you can feed at multiple points, you can also withdraw product at multiple points throughout the tower.

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Traditionally most columns have been built from a set of distinct trays or plates, trays maybe numbered from top down or bottom up either you name write the plate numbers from or stage number that is from the top you can write 1 2 3 4 5 and so on or you can also number from bottom which you can do other way round. So, either you can numbered from top or you can numbered from bottom when analysing a stage flows and composition take the number of the trays they leave the top tray of column tray one and numbers downwards this is the general convention.

So, you give a tray name number at top as 1 and then you go downwards 2 3 4 that is the usual convention, but you can use the reverse way as well and as it said when we analyse the stage flows and compositions take the number of that tray they leave. Suppose if you consider this is nth tray, so the component which will leave from here that is the vapour which will go off that will be y n and the liquid which will go down from this tray will be y x n of the more volatile component.
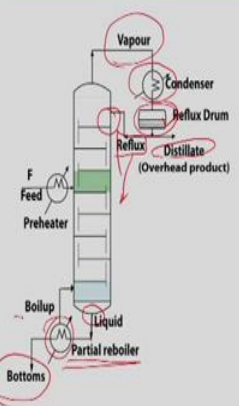
So, the component composition takes this number and similarly the into this tray like which will come say if we numbered from top to bottom. So, this will be n plus 1 th tray and from here the vapour will go to the nth tray. So, the in to the stray would be y n plus 1, and the liquid will come from top of this tray that is the n minus 1. So, the liquid which will into this nth tray would be composition of n x n minus 1. So, this way the flows and composition are numbered for a particular tray.

The liquid streams flows down the column from one tray to the next tray, and then the book vapour flows up bubbling through the liquid on the trays.

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Now, the vapour from top tray is condensed and the condensate is collected in a reflux drum, you can see the vapour which is coming at the top of the column there is a condenser here and there is a reflux drum over here. So, where you condense the vapour with the condenser and then goes to the reflux drum. So, this is reflux drum, a part of this liquid is drawn as the top product. So, which is the product over here is distillate and the other part is fed back to the top tray that is top tray is marked as number 1 so which is over here. So, enter at the top tray as a reflux; so we call this no returning the feedback to the column of top tray is named as reflux.

The top products contains the more volatile component A and a little of the less volatile B. So, mostly the more volatile component will come with the vapour phase with a very little of the less volatile components. So, e it will be richer in the more volatile component the liquid from the bottom tray goes to a reboiler where it is partially vaporized. So, you can see that from the liquid at the bottom which is coming out it goes to a reboiler where it is heated up, and it is partially vaporised so it is used partial reboiler.
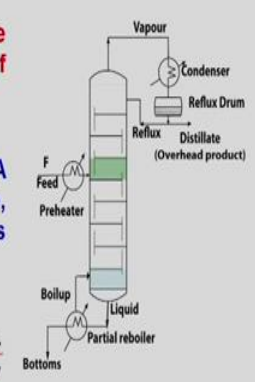
So, partially vaporized the vapour is fed back to the tower the liquid part is continuously withdrawn as the bottom of the product. So, bottom product over here is taken as

bottoms and the vapour partly of the vapour which is returned back to the column is known as the boiler. The bottom product is rich in the less volatile component B and has only a small amount of A in it.
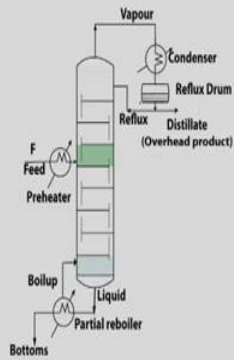
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So, A is the more volatile component; obviously, it will go with the distillate and the bottoms will be rich in the less volatile components transport of more volatile component of occurs from the liquid to the vapour phase while transport of the less volatile B occurs from the vapour to the liquid phase. So, throughout the column this phenomena from bottom to top takes place, the more volatile components leaves from the liquid phase to the vapour phase and less volatile component moves from the vapour phase to the liquid phase.

Thus a distillation column involves counter diffusion of the components not necessarily equimolar. So, distillation involves counter diffusion of the components and it may not be eqimolar counter diffusion because the heavier components or the less volatile component transferred from the vapour phase two to the liquid phase and more volatile component transferred from the liquid phase to the vapour phase in the in the distillation process that is why it is a counter diffusion of the components.
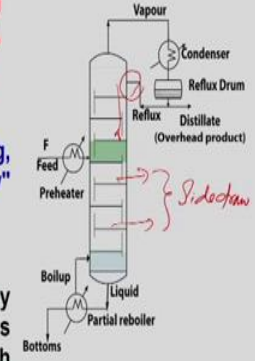
As the vapour flows up it becomes progressively richer in A similarly the liquid becomes richer in less volatile B as it flows down the column. So, it is now clear that the vapour flows up liquid flows down and then the component of the more volatile and less volatile changes with the you know liquid composition less volatile components and in the vapour phase more volatile component. The product leaving the top of the column is called the overhead product or it is called overhead and also it can be called as top product or it can be called as distillate or distillate product. So, any name can be adopted; distillate product maybe liquid or vapour or occasionally both.

So, you can have liquid vapour mixture or you can have only liquid or you can have only vapour, depending on the type of condenser you use. So, if you use total condenser that is all the vapours are condensed. So, then you will get as a liquid or if you use partial condenser. So, it will be vapour liquid mixer, most of the time the distillate flow rate is assigned the symbol D, and the composition is x D or y D depending on the product you are taking out.
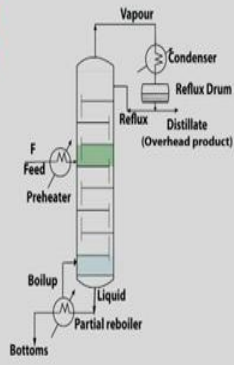
The product leaving the bottom of the column is called the bottom products or bottoms and given the symbol B with composition x B, in some situations notably petroleum refining one or more intermediate or side draw. So, side draw products may be removed from the column. So, in general for petroleum refinery one or more intermediate or side draw which is product is taken out from the side so that is called side draw. The portion of the column above the feed tray is called the rectification section and in this section the vapour is enriched by contact with the reflux.

So, in this case what happens we have a feed tray and above the feed tray we call that section is the rectifying section or enriching section what happens in this case the more volatile component because in this section the reflux from the top of the tray is comes down and vapour goes off and there is a contact between the reflux and the reflux and the vapour which is travelling upwards. In this section the vapour is enriched by contact with the reflux. So, vapour phase will be richer in the more volatile component in this section.
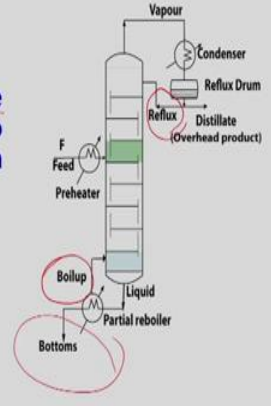
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The portion of the column which is below the feed tray is called the stripping section, the liquid portions of the feed serves as the reflux of this section in the bottom section is called feed either some of the feed as well as the reflux, which is coming out from the top they serve as the liquid flow below the feed tray, and that is called the striping section. The operating pressure of the column is typically controlled by adjusting heat removal in the condenser.

So, depending on the pressure you want you can just control pressure by operating the condenser heat removal over here. A normal column has a temperature gradient and a pressure gradient from bottom to top. So, inside the tower the liquid and vapours are always at their bubble points and dew points. So, the highest temperature is at the bottom and the lowest temperature is at the top. So, there is temperature gradient throughout the column and bottom of the column will have the highest temperature and it gradually decrease and the lowest temperature would be at the top of the tower.

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So, the entire device including both the sections that is you know rectifying section and the stripping section is called the fractionators. In normal operations there are five handles that can be adjusted to manipulate the behaviour of a distillation column. So, we can change the behaviour of the distillation column by adjusting five handles what are them the feed flow we can change the feed flow we can also to product flows.

So, bottom products depending on our requirement we can take and also the distillate which is we are taking out at the product, at the top that we can change or we can manipulate. The reflux flow the reflux ratio we can change, we can use variable reflux ratio by changing different reflux to the column and we can also change the boil up flow or reboiler heat input. So, this flow also we can change. So, these are the five handles in a distillation column for normal operation, we can adjust them or manipulate them to see the behaviour of the distillation column.

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Now, we will consider ideal stages. An ideal stage is one where the vapour and liquid leave the stage are in equilibrium. So, as we said earlier for any tray there is a liquid a level maintained and the vapour from the bottom goes through the perforation of the plates and there are different plate designs we have already discussed. So, it flows through the liquid and there is a intimate mixing between the gas and liquid on that liquid pool and after that it engage from the liquid and goes to the next stage.

So, because of this the vapour and liquid which leaves a particular tray they are in equilibrium. So, leave the living streams are in equilibrium not the incoming stream to the tray. So, the living stream should be in equilibrium, consequently the vapour composition fractionally depends on the liquid composition. Ideality is an approximation, but stage efficiency can be used to account for real cases.
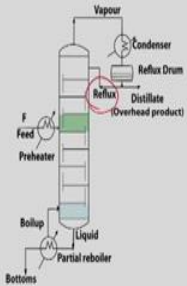
So, if we assume that equilibrium is reached and it is separation happens till the equilibrium is reached. So, then we call it as ideal stage, but actually it may not reach the ideal no equilibrium conditions in each stage and there is a deviation from the equilibrium. So, in that case to find out the real number of stage required for a particular separation we use stage efficiencies. A key result of the ideal stage assumption is that the liquid streams living an ideal stage or assume to be at their bubble point and vapour steam leave at their dew point. So, that is the important assumption for an ideal stage,

that is the liquid stream leaving an ideal stage or assume to be at their bubble point and the vapour which is leaves from the tray will be at their dew point if it is ideal tray.

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So, when no azeotropes are present both top and bottom products may be obtained in any desired purity if enough stages are provided and enough reflux is available. So, depending on the number of stages and depending on the reflux any desired purity of the product we want we can achieve using distillation. In practice there are limits to the number of stages and to the amount of reflux. So, not every separation can be accomplished so, because of this limits design limits of number of stages and the amount of reflux you can know vary so based on that you may not be able to apply distillation process for every separation.

Theoretical limits of performance are imposed by total reflux that is minimum stages and minimum reflux that is infinite number of ideal stages. So, we will discuss this total reflux and minimum reflux later that now theoretical limit it says whatever the vapour produce at the top of the column, if you condense completely and completely returned as a reflux without taking out any product in that case we will get the minimum mm number of stages required to do a particular separation. And if we give a very less reflux or very small reflux that is the minimum reflux then the number of stages required we can we can calculate theoretically and we will see that infinite number of stages are required for a particular separation.

So, depending on the reflux ratio we use or reflux we use it gives theoretical limits of minimum stage and the maximum stage that is the ideal stages. So, this we will discuss in the later part.

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Now, we will discuss about the condenser and reboiler, there are two main categories of condenser differentiated by the extent of condensation. As we said one is total condenser in the total condenser all the vapour no leaving the top of the column is condense. So, the vapour which is coming out over here if it is total condenser all the vapours are condensed to the liquid phase; consequently the composition of the vapour leaving the top tray suppose this is leaving and its composition is y 1 because this vapour is coming from tray number one say. So, y 1 is the same as that of the liquid distillate product and reflux x D.

So, the distillate because it is completely all the vapours are condensed so, the reflux composition and the distillate composition would be same with respect to y 1. So, y 1 would be equal to x D the another kind of no condenser which is used is partial condenser the vapour is only partially liquefied the liquid produced is return to the column as liquid and a vapour products stream is removed.

So, you take a vapour liquid mixture you just take the vapour and partially condense it. So, in the reflux drum you will have a vapour component and you have a liquid components and then the vapour products steam is removed and the composition of this
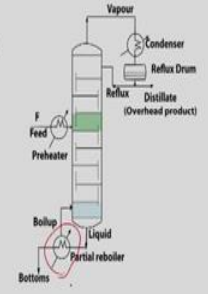
streams that is V 1 D and R are difference. So, the vapour which is coming here the composition over here and then the distillate you are taking here that is over here, and the reflux you are giving they are of different composition.

Normally D having the composition of the distillate having composition of y D is in equilibrium with the R that is composition x D. So, because they are in equilibrium if you take a vapour you know product over here in the reflux drum that also can be considered as one equilibrium stage because vapour and liquid they exist in a drum. So, you are taking the vapour product as y D and the reflux you are giving as a liquid as vapour which has composition y D and you have reflux which has composition x D. So, they are in equilibrium composition.

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So, a partial condenser functions as an equilibrium separation stage. So, column with a partial condenser effectively have an extra ideal stage. So, when you calculate the number of ideal stages, then if it is partial condenser you have to calculate reflux drum as an extra equilibrium stage. Now regarding reboilers, most reboilers are generally partial reboilers they only vaporize part of the liquid in the column base.

So, here so part of the liquid is vaporized which is return to the column and the liquid is taken as a bottom product, partial reboilers also provide an ideal separation stage. So, in the reboiler also there is a intimate contact between the vapour phase and the liquid phase. So, this is also considered to be one equilibrium stage or ideal stage.

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Now, reboiler take different kinds of forms one of them is the thermo siphon type that rely on the thermal effect on density to draw liquid through the heat exchanger. So, basically you need not to create you know or pump the liquid vaporised and to the column you know returning the column to the as a vapour, you need not to pump it because of heating eff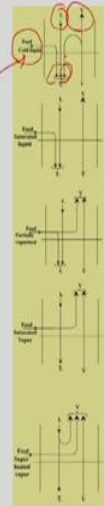ect or thermal effect and. So, effect on the density of the liquid which will draw to the heat exchanger it will automatically circulate if you use the thermo siphon type reboiler. Another is called the forced circulation type that use a pump to force the liquid through. So, you use a pump over here and you take the liquid from the bottom of the column and force to the re reboiler, heat it and then the vapour will go to the boil up vapour will go as boil up and you can get a bottom products.

Another is called the stab in type that come through the side of the column in to the liquid reservoir. So, stab in type that is a no most of the refineries you will have similar kind of reboilers, stab in type in large complex column side stream reboilers can be also used. So, basically this you will get in petroleum refinery. So, this side steam mm reboiler are generally used and there are large and complex columns in the refineries, these draw liquid of a tray heat it and then return the vapour liquid mixture to the same or a similar tray. So, it takes the liquid out from a particular tray and then it heat it off and then it return to the same tray or in the similar tray. So, this is called side stream reboiler.

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Now, thermal condition of the feed determines the column internal flows. So, we will look into the feed conditions and how it you know changes the flows of the vapour and liquid in the column internals. So, this is very important to understand as you can see over here the if the feed is below its bubble point; that means, it is a cold feed which is shown over here heat is needed to raise it to where it can be vaporised.

So, since it is a you know feed is below the bubble point. So, this feed will need to heat of where the it will be vaporized the more volatile component will come out. So, what will happen in this case there is a liquid flow from the top of the column which is coming over here and since this feed is cold feed the vapour which is going off some of part of the vapour it will condense. And along with the reflux a liquid or the you know liquid which is coming down to the upper tray of the feed tray.
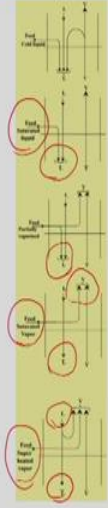
So, the total column internal liquid flow below the feed tray will increase and then the vapour flows towards the top of this column here will decrease because part of the vapour is condense to heat the you know cold feed, this heat must be obtained by condensing vapour raising through the column. So, the liquid flow moving down the column increases. So, this is a case where you have a feed below its bubble point.

So, how much it will increase? By the entire amount of liquid feed which is given over here liquid feed plus the condense material which is condensed from the vapour and the vapour flow upward is decreased.

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Now, let us consider the second case, if the feed enters as superheated vapour that is above its dew point. So, feed enters as superheated vapour and it will vaporize some of the liquid to equalise the enthalpy so which is shown over here the superheated vapour. So, what will happen because it is vapour and it is also at very high temperature? So, the liquid which is coming down will also be a part of this will also be vaporized and it will add with the vapour flows which is coming from the downward tray so in this case the liquid flow down the columns drops.

So, this will decrease and the vapour flows up towards the column will increase and that will increase by the entire amount of the feed because that is the superheated vapour call amount of the feed plus the vaporised material which will come from the liquid vaporization. So, that will be the add up to the vapour flows which is already coming, if the feed is saturated liquid or vapour no additional heat must be added or subtracted and the feed adds directly to the liquid or vapour flows.

So, if you take super heated saturated vapour so, basically all the liquids; so, you this vapour need not to heat the liquid which is coming down. So, it will just directly add with the vapour which is coming down. So, with the entire amount of the feed and liquid flows will not change towards the below the feed tray where as the vapour flows will an increase by the amount of the feed flow and similarly if you take the saturated liquid. So in that case what will happen? Your liquid does not need to heat it up and. So, the vapour

flows as it is it will flow and the vapour flows above the feed tray will not change; however, the liquid flow will increase by the amount of the feed flow.

Now, there is another case if you take the feed partially vaporized. So, it depends on the vapour and liquid composition. So, from the feed the amount of vapour which is present in the feed will add up with the vapour and the amount of liquid present in the feed will add up with the liquid. So, the feed will be distributed to vapour phase and the liquid phase and the flow rate will be accordingly enhanced.

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Now, we will discuss the number of trays by McCabe-Thiele method. There are some assumptions you know we will just discuss the fundamentals of McCabe-Thiele method for determining the number of trays that is the graphical method. And to do so we need to have few assumptions, the first assumption is that the most important assumption which is underlying for the McCabe-Thiele method is the molar rate of overflow of the liquid from one tray to the another is constant over any section of the column.

So, the first assumption and that is most important assumption is that the molar flow rate of the liquid in all sections of the column remains constant. So, with this assumptions if we consider the feed entry at the top the liquid from the top column is l naught and that should I will change to l 1 l 2 up to l n. So, all this flow rate in each tray they will be equal and. So, we can write as l by removing the subscript and we call it constant in the rectifying section. So, in the rectifying section the tray number maybe number 1 2 3 up

to l n. So, this will be the liquid flows can be termed as l in the rectifying section. Similarly stripping section that is below the feed tray we can name the tray number as L m bar which would be equal to L m plus 1 bar and up to L N L capital N and that should be equal to L bar so which is constant in the stripping section.

The constant flow rate of the liquid or vapour in the two sections differ by the rate of input of liquid or vapour feed to the column at the feed tray. So, as we have discussed before we depending on the feed condition or the either it is vapour or liquid or it is a vapour liquid mixture depending on the feed the constant flow rates of the liquid and vapour in the two sections will change.

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The second assumption for the McCabe-Thiele method is that the molar vapour rates in the respective sections are also remain invariant or constant and this is assumption is popularly known as Constant Molar Overflow CMO. The assumption is obviously, true when the molar heat of vaporization of the mixture does not depend upon the temperature in the column.

So, this assumption that is constant molar overflow for the vapour will be true when the molar heat of vaporization of the mixture will does not depend upon the composition or the temperature in the column for example, a mixture of hydrocarbons not deferring much in the molecular weight. So, in that case this assumptions may be true, for many liquid mixtures the assumptions is also a good approximation if constant molar overflow

occurs the mass exchange between the phases occur in the equimolar counter diffusion mode.

So, please note that if constant molar overflow occurs the mass exchange between the phases occur in the equimolar counter diffusion mode. So, that is based on this equimolar counter constant molar overflow. So, if this assumption is valid then the mass exchange between the vapour phase and the liquid phase should be based on the equimolar counter diffusion.
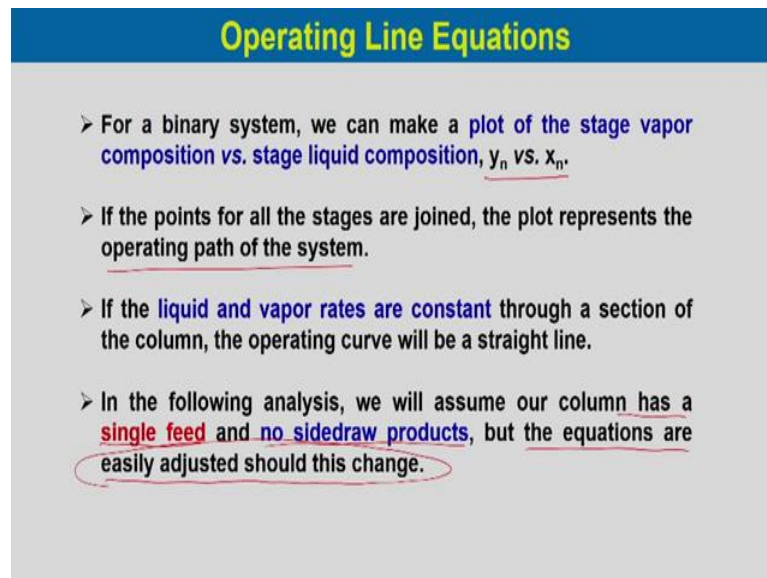
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The third assumption over here is heat loss from the column is negligible. So, this is also another important assumption for McCabe-Thiele method there is heat loss from the column. So, it is to be noted that if there is heat loss or gain there will be accompanying condensation or vaporization within the column and the flow rates will vary along the column as a results. So, this assumption is also very important if there is heat loss and gain there will be condensation or vaporization inside the column; so, which will change the column internal flows.

Major step of the graphical construction in the McCabe-Thiele method are as follows the first is draw the equilibrium curve using the available equilibrium data ok, either equilibrium data or some correlations would be available to draw the equilibrium curve. The second thing is the draw the operating lines for both the sections, one is rectifying

section another is stripping section then draw steps between the equilibrium curve and the operating lines to find out the number of ideal trays.

So, this graphical methods of finding out the number of trays or number of ideal trays required we will discuss later, but we will go systematically to find out the operating line equation and operating line for the stripping section and the rectifying sections, we will discuss on that part first.
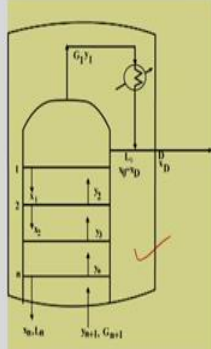
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Now, operating line equations for a binary system we can make a plot of the stage vapour composition versus stage liquid composition that is y n verses x n. If the points for the all the stages are joined the plots represents the operating path of the systems. If the liquid and vapour rate are constant through a section of the column the operating curve will be a straight line. In the following analysis we will assume our column has a single feed no side draw products, but the equations can be easily adjusted should this change. So, no side draw product single feed, when we have a multiple feed or we have a side draw products these equations can be easily adjusted to that conditions that we will discuss in the later part of our a lectures.

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Now, we will consider the rectifying section to find out the operating lines and consider total condenser. So, the reflux at the bubble points, consider a section of the fractionator entirely above the point of introduction of heat. So, this is above the introduction of the feed which is shown over here and the condenser removes all the latent heat, but does not cool the resulting liquid further; so it is at their bubble points.

Therefore, the reflux and distillate products are liquids at their bubble points, let L be the downward flow of the liquid from each tray and G is the raising vapour from each tray in mole per hour.

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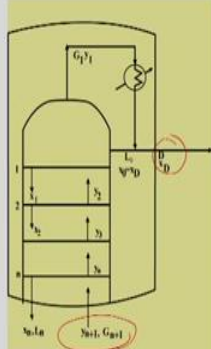Now, a total material balance over the envelope we can write is G would be equal to L plus D and let us define the reflux ratio which is R is equal to L by D. So, we can write G would be from, here if we just substitute no L from here L is equal to R D. So, if we substitute in this no to total material balance envelope. So, reflux which we have defined R is equal to L by D that is the amount which is return is and the distillate which is taken out L by D. So, G would be equal to R D plus D which is equal to D into R plus 1 and from that we can get G by D would be equal to R plus 1.

Equation that represents the material balance of component A over an envelope shown over here. So, that is G y n plus 1 over here because all the flow rate the gas and liquid flow rate they are taken as constant. So, it is you know subscript are taken off. So, G into y n plus 1 would be equal to L x n plus D x D. So, this is the material balance for component A.

Operating Line Equations

Rectifying Section (Total Condenser – reflux at the bubble points):

$$Gy_{n+1} = Lx_n + Dx_D$$

$$\Rightarrow \quad y_{n+1} = \frac{L}{G}x_n + \frac{D}{G}x_D = \frac{L/D}{G/D}x_n + \frac{x_D}{G/D}$$

$$\Rightarrow \quad \boxed{y_{n+1} = \frac{R}{R+1}x_n + \frac{x_D}{R+1}} \quad since \ \frac{G}{D} = R+1$$

$$R = L/D$$

- This is the equation of a straight line on the x-y plane with a slope $R/(R+1)$ and an intercept $x_D/(R+1)$ on the y-axis.

- Also, the equation is satisfied by the point $x_n = x_D, y_{n+1} = x_D$

Now, from this if we rearrange if we substitute divide G for both the left and right hand side of this equation we would obtain y n plus 1 would be equal to L by G x n plus D by G x D. now if we substitute here this will be L by D divided by G by D into x n plus x D divided by G by D. So, from here we can write since G by D is R plus 1 and R is equal to L by D, we can write y n plus 1 would be equal to R by R plus 1 x n plus x d by r plus 1.

So, this equation of, this is the equation of the straight line on the x y plane with a slope R by R plus 1 and an intercept is x D by R plus 1 on the y axis. Also the equation is satisfied with a x n would be equal to x D and y n plus 1 would be equal to x D. So, this two point must be satisfied with this equation of straight line. So, this is the operating line equation in the rectifying section.
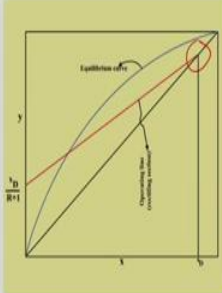
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Operating Line Equations

Rectifying Section (Total Condenser – reflux at the bubble points):

- So the straight line passes through the point (x_D, x_D) which is a point (say D) on the diagonal.

$$y_{n+1} = \frac{R}{R+1}x_n + \left(\frac{x_D}{R+1}\right)$$

- This equation is the *operating equation* for the rectifying section of the column.

- It is called an operating line because it relates the **concentrations of the liquid and the vapour phases leaving or entering a section.**

So, the straight line passes through the point x D x D which is a point say D over here and with the point x D x D and on the diagonal over here we have the intercept x D by plus 1. So, we will have the operating line equation for the rectifying section. It is called an operating line because it relates the concentration of the liquid and the vapour phases living or entering a section. So, that is why it is called operating line.