Process Equipment Design
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Lecture –48
Distillation Column – 1

Hello everyone. This is 48th lecture of the course Process Equipment Design and here we are going to start discussion on distillation column. So, as far as this topic is concerned here in this course we will cover the process design as well as mechanical design of distillation column also. So, first of all we will focus on process design. So, this topic distillation column you have already covered in your BTech that is maybe second year mass transfer course.

And in this course we will start from where you have stopped here. It means some of the points we will recall from the basic course so that can be further used in design of distillation column. So, let us revise this topic quickly, but before that let me focus on the content which I am going to cover in this course related to distillation column.

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So, here we can have the distillation column, process design. First of all I am focusing on the process design and then we will proceed for mechanical design. So, in the process design we will start with the distillation and the continues process. It means here I will quickly cover the topic which you have already read. So, some revision will be done over here and then we will design the binary system. So, this part you also have covered.

So, we will cover this very quickly and then we can consider multi component system. So, in your BTech second year course you may not have done this so that will be covered over here. And now once I am having the multi component system we will focus on plate efficiency. So, as far as plate efficiency is concerned some points about that you already know that we have point efficiency, Murphree plate efficiency etcetera.

But here we are going to discuss plate efficiency in very detailed manner and finally we can have the topic plate hydraulic design, how to design the plate of a particular distillation column. So, in this way the whole process design will be covered. So, let us quickly revise the distillation and the continuous process.

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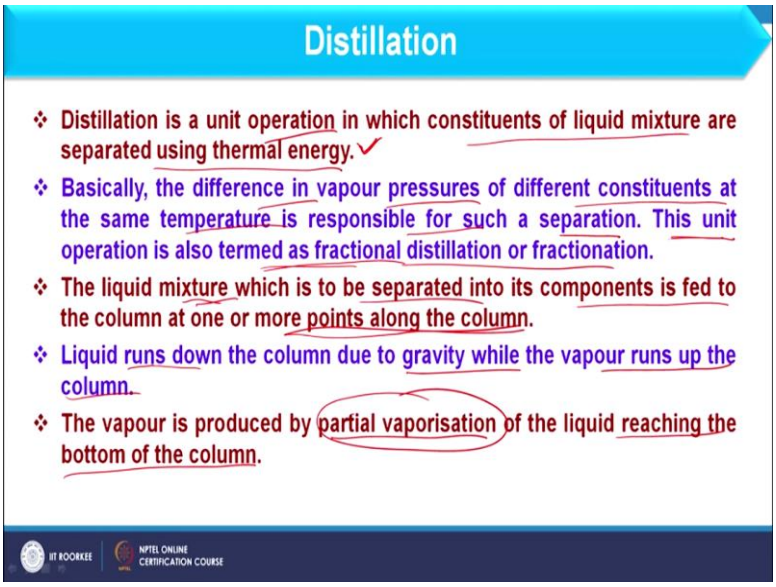

So, as far as distillation is concerned it is basically the unit operation in which constituents of the liquid mixture are separated using thermal energy and that thermal energy we usually provide in the reboiler. So, basically the difference in vapour pressures of different constituents at the same temperature is responsible for such separation. This unit operation is also termed as fractional distillation or fractionation.

And further we can have the liquid mixture which is to be separated into its component and that should be fed to the column at one or more points along the column. It means we can have the multiple feed system and distillation column and accordingly we can choose the insertion of the feed. In the distillation column, we observe that liquid usually runs down the column due to gravity whole vapour moves up which is the natural movement of vapour as well as liquid.

And vapour is produced by partial vapourization of the liquid reaching the bottom of the column. So, here you can consider this partial vapourization is usually occur in reboilers.

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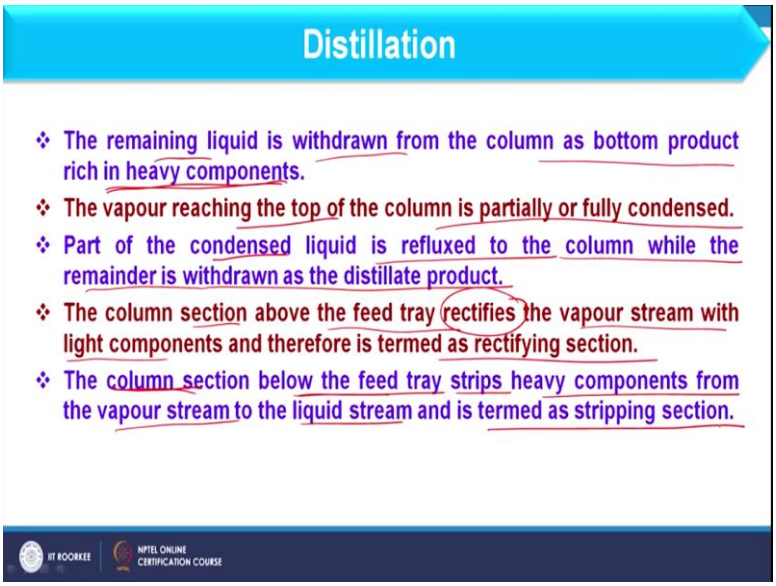

So, further the liquid which is remained is withdrawn from the column as bottom product and that contains basically heavy component. I hope you understand the meaning of light component and heavy component which is lighter it means which has more volatility that will be consider as lighter product or lighter component which has lesser volatility. It will be consider as heavy component.

And you understand that in distillation column from top we usually have light component and from bottom we usually get heavy component. So, vapour reaching the top of the column is partially or fully condensed. Part of the condensed liquid is refluxed to the column while remaining we can withdraw as a distillate product. So, all these points, you know, but we are quickly covering it.

And further we have column section above the feed tray which we consider as rectifier section or rectifying section basically. So, it rectifies the vapour stream with light components and therefore we consider this as a rectifying section or rectification. In the similar line, the column section below the feed tray strips heavy component from vapour stream to liquid stream and it is termed as the stripping section.

So, in this way we basically have lighter product as distillate and heavy product as bottom. So, let us focus on the continuous process.

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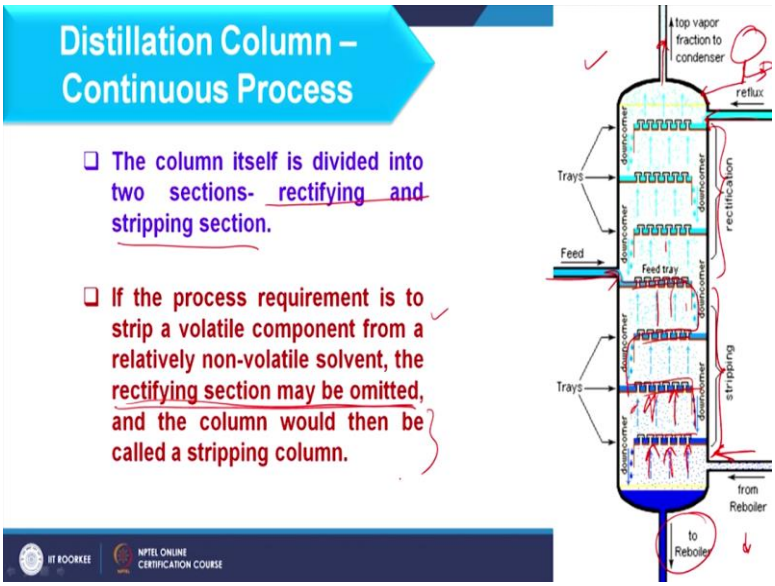

If you consider this schematic here we have the feed which is entering into the distillation column and on each tray mass transfer occurs between liquid and vapour. So, liquid moves in this way and vapour moves from the middle you can see here as you can see the arrows are shown upward. So, the section below the feed tray we consider that as a stripping section and this is rectifying section.

And from top we have vapour which is entering into the condenser and from condenser we can get product as distillate and from here we can have the reflux also and that is basically returning back to the distillation column as liquid. Similarly, from bottom liquid enters into the reboiler whatever vapour is generated it is entering to the column and from reboiler we can get the bottom product out.

So, it has basically two sections rectifying and stripping section that we have discussed already. If the process requirement is to strip a volatile component from relatively non volatile component the rectification section can be removed and column can be considered only as a stripping column. So, continuous operation we can have, but usually the contact occurs in batch wise over the tray, but in this way we consider the continuous distillation column.

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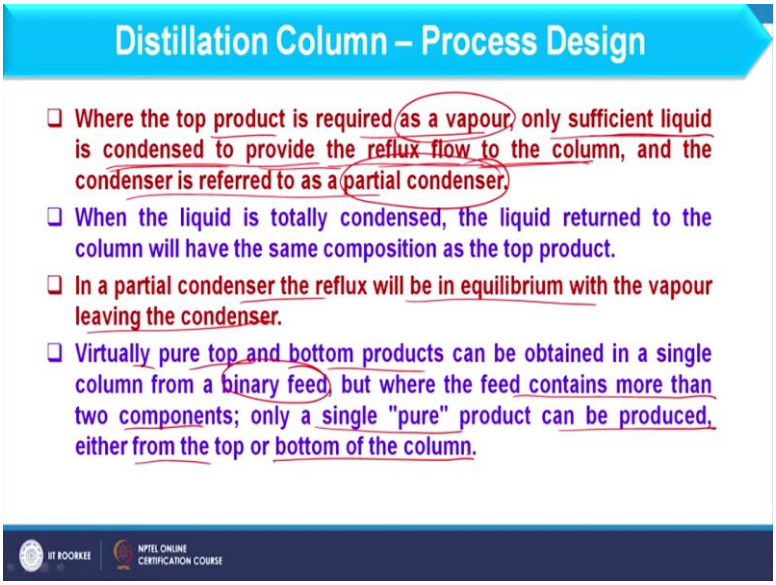

So, further in distillation column where the top product is required as vapour when I am considering the distillate at the top if that is required at the vapour only sufficient liquid is condensed to provide the reflux flow to the column and condenser is referred as the partial condenser and this point we have also discussed when we were discussing the topic of condensation and design of condensers.

So, when product is required in the form of vapour certain amount of vapour which is exiting the distillation column is converted into the condenser and that condensate recycles back to the distillation column as reflux because distillation column always require a liquid stream which can be obtained through reflux only and if I am having the top product as liquid phase and reflux will also be in a liquid phase we can consider that total condensation is required.

And in that case it is called total condenser. In partial condenser, reflux will be in equilibrium with the vapour which is leaving the condenser. So, we can consider all these points as well as operation in a distillation column is concerned and we can also consider that virtually pure top and bottom product if we want to obtain that is possible when I am considering binary feed.

But if I am having more component than to in the feed only a single pure product can be obtained either from the top or bottom of the column or usually have mixture at the top as well as bottom. So, this condition we call as multi component system and we will focus on the design of multi component system in this course also. As you know that reflux is required

to maintain sufficient liquid in the distillation column, but what reflux ratio we should consider.

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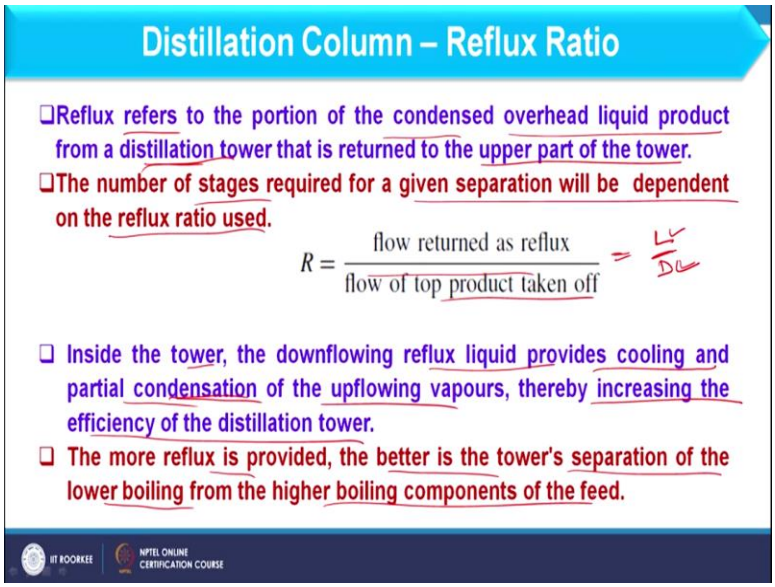

So this point we have already discussed that reflux refers to the portion of the condensed overhead liquid product which is coming to the distillation column and it is basically returning at upper part of the column. And the number of stages required for the given separation will depend on the reflux ratio. As we have variation in reflux ratio, we can consider different number of stages in plate column.

So that you also have read with the binary system which we are going to cover in this lecture where you can find that based on reflux ratio only number of stages can be decided in McCabe Thiele method. I hope you remember that method. So, as far as reflux ratio is concerned that is the flow which is returned as the reflux divided by top of the product taken off.

So, it is basically L / D if we need to represent that mathematically. So, that is L which is returning back to the column and D is the total distillate. So, inside the tower down flowing reflux liquid provides cooling and partial condensation of the upflowing vapour and thereby increasing the efficiency of the distillation tower. So, when we provide more reflux better is the tower separation of low boiling from the high boiling components of the feed.

So, in this way we consider the reflux ratio as important parameter and let us see how to find out the reflux ratio and what are the different reflux ratio available?

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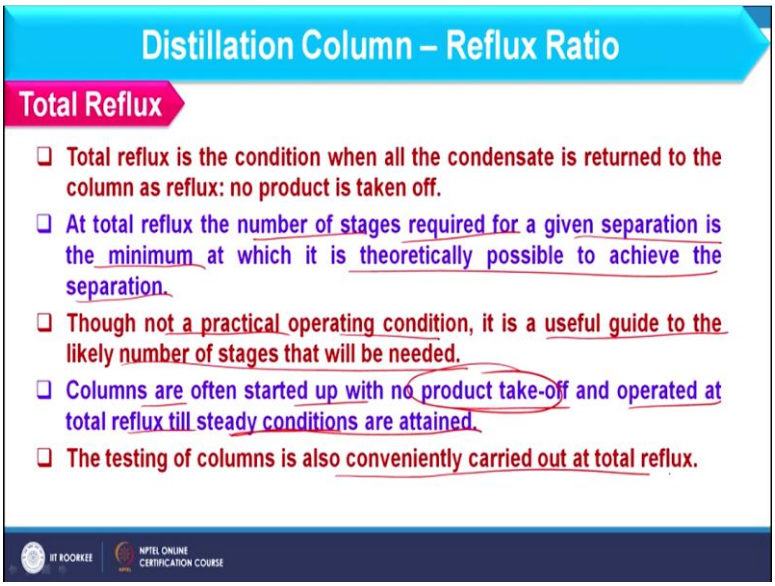

The first one is the total reflux. So, when I am considering the total reflux it means all condensate is returning back to the column. And in that case we are not considering any product which is exiting the distillation column from top. So, distillate will be zero so R value should be infinite. So, in that case distillate will be zero. So, total vapour which is exiting it is converted into condensate and that is returning back to the column.

Now, if this is the case that we consider as total reflux. In this case, number of stages required for the given separation is minimum at which it is theoretically possible to achieve the separation. So, total reflux gives the minimum number of plates in the distillation column. Though, not a practical operating condition it is useful guide to likely number of stages that will be needed.

So, when we consider the optimization of reflux ratio we should need minimum number of stages and we should need maximum number of stages. So, total reflux will give the minimum number of stages required for the given separation. Columns are often started up with no product take off and operated at total reflux till steady state conditions are attained. So, that also happens, but only with the start of the process not after that and testing of the column is also conveniently carried out at total reflux condition.

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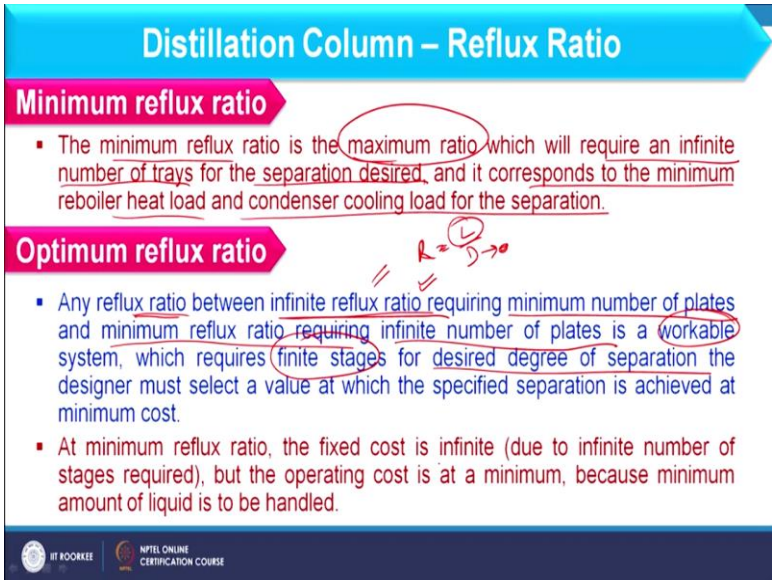

And now we have minimum reflux ratio if I am having total reflux we can consider minimum number of stages. Minimum reflux gives maximum number of stages. So, basically minimum reflux ratio we consider as the maximum ratio at which we require infinite number of trays for the given separation and it corresponds to the minimum reboiler heat load and condenser cooling load for the separation.

So, in that case if I am having minimum reflux ratio we have minimum duty in reboiler as well as condenser. So, if I consider this condition it means the number of plates will be infinite it means the capital investment we are doing in distillation column that will be very high or that will be we can say as infinite. However, the load of the reboiler as well as condenser is minimum.

So, we can consider the capital investment in reboiler and condenser is minimum. So, there are two things which are moving opposite to each other. And that we will consider in optimization of the reflux ratio and next we have the optimum reflux ratio. Any reflux ratio between infinite reflux ratio or we can consider this as the total reflux and why I am considering this as infinite? Because if R is equal to L / D if I am not taking any product out so D would be 0.

So, we can have R as infinite value. So, that is also the condition with total reflux. It requires minimum number of plates and minimum reflux ratio require infinite number of plates and we have to work between these two. So, we have to find the finite stages for desired degree of

separation and for that we should select the optimum reflux ratio based on economic decision.

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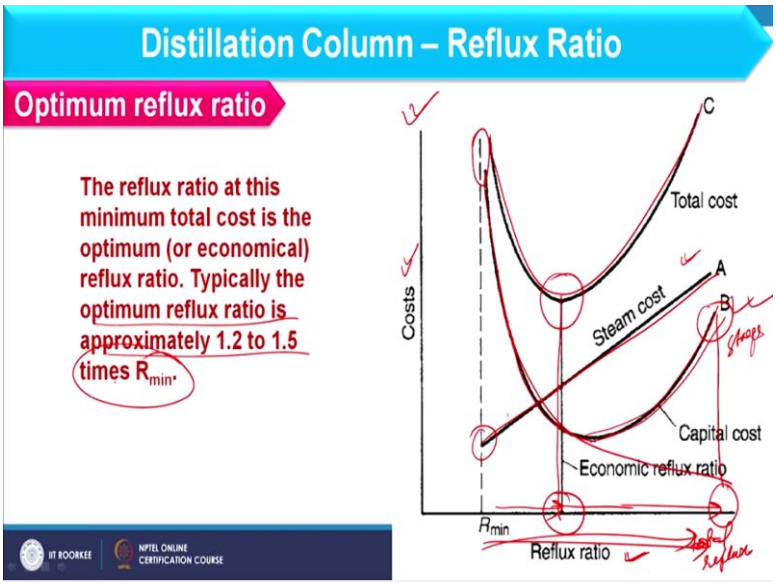

So, let us see how to find out optimum reflux ratio. If you consider here we have the graph between cost as well as reflux ratio. So, if I have the minimum reflux ratio we already have discussed that capital investment will be infinite, but that capital investment will be in terms of number of stages not with the cost of reboiler as well as condenser, but number of stages will be too high that it will dominate over the cost of the reboiler as well as condenser.

So, when I am considering minimum reflux ratio at that point heat duty of reboiler and condenser will be minimum and so we can say the operating cost will be minimum. And so you can find this value where I am having the steam cost which should be minimum. And as we move further than the minimum reflux ratio, we can find that number of stages will keep on decreasing and when I am having total reflux ratio number of stages will be minimum.

So, in this way somewhere we can find if this is the total reflux we can find the minimum number of stages and capital cost due to stages will be least. However, at that time reboiler and condenser duty will not be less that will be maximum. So, in that case the capital cost of reboiler as well as condensate will dominate and so you can find that increment in capital investment. If this will be based on number of stages only it should be like this.

However, here it is increased which is due to the capital investment of reboiler as well as condenser. So, in this way we can consider the capital investment. However, as the heat duty

of reboiler and condenser increment in reflux ratio from minimum reflux to total reflux we can continuously find variation or increment in the operating cost and if we consider addition of these two we can find total annual cost.

And wherever it will give the minimum value this reflux ratio I can choose as the optimum reflux ratio. So, usually optimum reflux ratio is approximately 1.2 to 1.5 times minimum reflux ratio. So, in that way we can choose the optimum reflux ratio.

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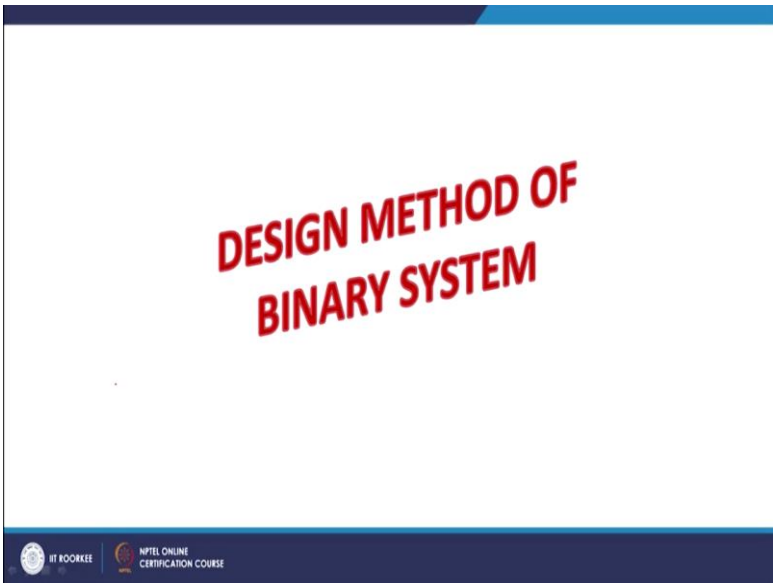

And now we will discuss the design of binary system. Why I am considering this because whatever balances we consider in binary system either mass balance or energy balance the same will be extrapolated to multi component system also. So, here we will revise the design of binary system assuming that you know this already.

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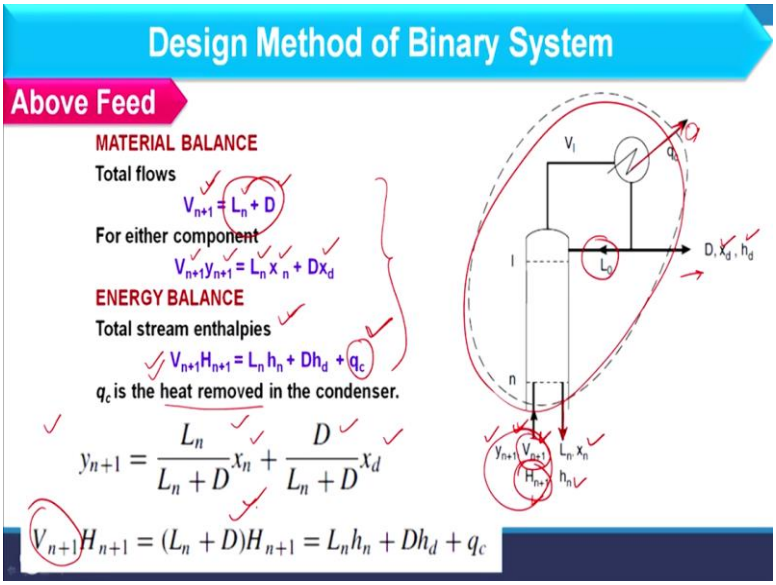

So, to start design of binary system let us make the material and energy balance. So, we are considering above feed system so here you can consider the distillate and this is basically the reflux and if we consider material and energy balance we usually make the envelope and in this envelope whatever stream is entering is that V n + 1 that is basically the vapour stream which is exiting n + 1th tray.

It has composition as y n + 1 and total enthalpy which is available in this is capital H n + 1. So, that you understand that for vapour we represent the total energy or total enthalpy in the form of capital H. In the similar line, streams which are leaving the system are L n available at h n at composition X n and another stream which is exiting the system is distillate at X d containing enthalpy h d.

So, making the material balance we can simply consider V n + 1 should be equal to L n + D simple balance is there and for component balance we can consider as V n + 1 into y n + 1 = L n into X n + D x d. In this way we can make the component as well as mass balance. Now we can make the energy balance. Total streams enthalpy because this is basically stream which is entering and that contains capital H n + 1 so this is the simple balance.

And here we are considering qc because qc heat which is released from the condenser it means this amount of heat is coming to the coolant from vapour stream. So, we consider that this heat is exiting the system. So, here you see qc is basically heat removed from the condenser that we have already discussed. Now, arranging these equations we can find the final equation as y n + 1 = L n / L n + D x n + D / L n + D x d.

So, in the similar line I can write the enthalpy balance also replacing this V n + 1 with this. So, we can find this expression. So, these are basically the equations for above feed condition.

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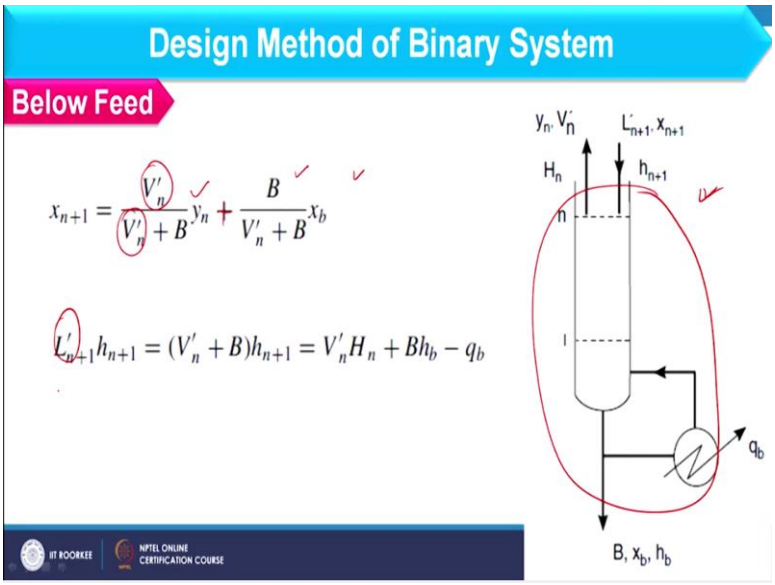

Now similarly we can find the balance at below feed and here we can make the balance and making the envelope like this. So, I am not going into detail of derivation of the equation. We can simply have the equation as x n + 1 which will be equal to V dash n / V dash n + B into y n and then plus and we can have B / V dash n + B into x b. So, you can see here we are representing the vapour flow rates as well as liquid flow rates with prime.

So, that is the basic representation of variables in above feed and below feed columns. So, below feed we usually consider prime above feed we consider without prime. So, in subsequent lectures also if this nomenclature is used you should understand which part I am focusing on.

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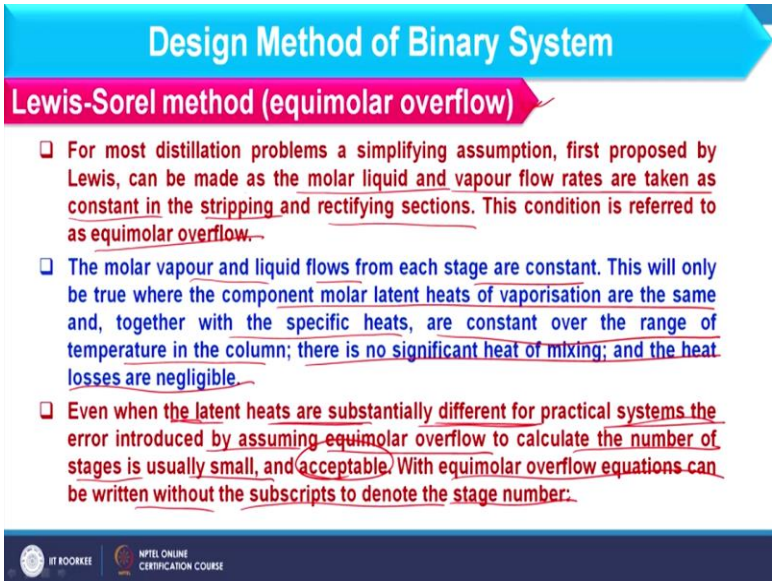

Now, further we can have some assumptions and based on that we will design the binary system. The assumption is like whatever molar flow rate we are considering either for liquid and vapour. So, these molar flow rate will be constant in each tray. So, throughout the distillation column these vapour flow rates as well as liquid flow rates will be constant. Like if I am considering L n or V n so that should be L and V throughout the distillation column.

And that assumption is basically given by Lewis. So, complete method we call as the Lewis Sorel Method and here the assumption is like molar liquid and vapour flow rates are taken as constant in stripping section and rectifying section and this condition we consider as equimolar overflow. So, the molar vapour and liquid flows from each tray are constant that is the assumption only.

And this will be true where component molar latent heat of vapourization are same and together with the specific heats are constant over the range of temperature in the column and there is no significant heat of mixing and heat losses are also negligible. Further, even when latent heats are substantially different for the practical system the error introduced by assuming equimolar overflow to calculate number of stages is usually small.

And that can be acceptable also. So, with equimolar overflow equation can be written without the subscript to denote the stage number.

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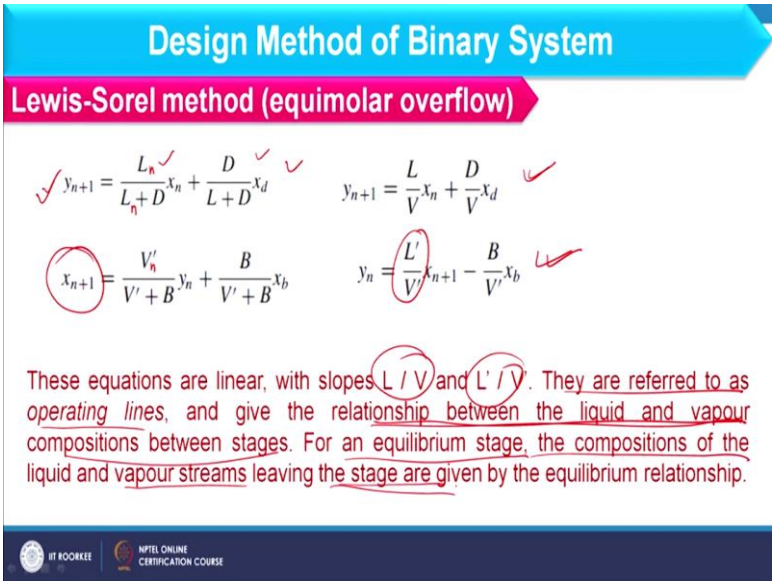

So, when I am assuming this we can represent the equations like y n + 1 should be equal to L / L + D into x n and additionally we further consider D / L + D x d. So, you can see we are not considering n over here like this. So, this should not be considered because equimolar overflow we have assumed. And when we resolve this equation we can obtain equation like this and when we consider this equation we can find revised equation as like this simply rearranging and considering the balances.

So, in these equation L / V and L dash / V dash are basically the slopes and they are referred as the operating lines and give relationship between the liquid and the vapour composition between stages for an equilibrium stage the composition of liquid and vapour streams leaving the stage are given by equilibrium relationship. So, these are some points which we have to discuss to design the binary system and here we are having McCabe Thiele method. So, let us see the steps to be followed in this method.

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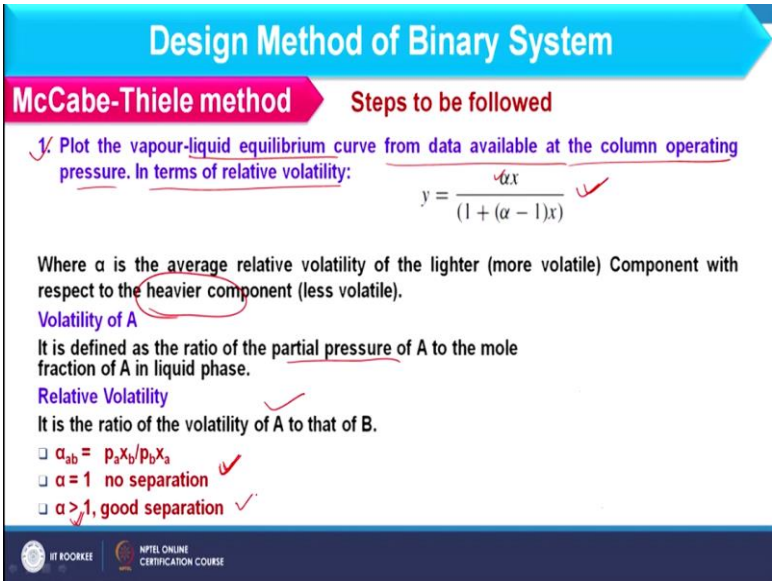

So, initially we have to plot the vapour liquid equilibrium curve from the data available at the column operating pressure and in terms of relative volatility and we can consider that equilibrium curve with this equation. So, where alpha is basically the relative volatility of lighter component and that relation we consider with respect to heavy component. So, you can see here I am having mol fraction in vapour that is y as well as x on x axis.

And if you see this is basically the equilibrium line and joining these two point will give this line. So, volatility of A it is defined as the ratio of partial pressure of A to the mol fraction of A in the liquid phase. And relative volatility it is the ratio of volatility of A to that of B. So, you can consider these equations when I am having alpha = 1 it means no separation occurs and when alpha is there which is greater than 1 we consider that as good separation condition.

So, these are some nomenclature which we consider in McCabe Thiele method or distillation column designing.

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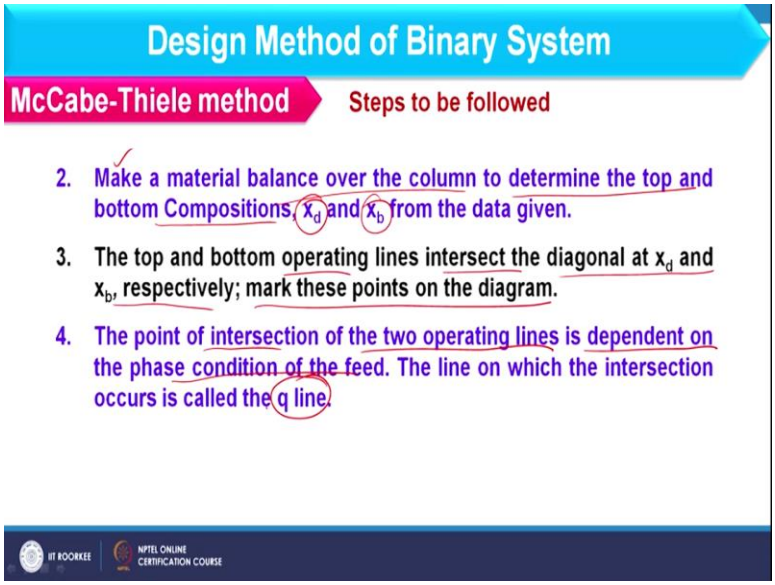

And further second step is to make the material balance over the column to determine top and bottom composition that is x d as well as x b from the given data. The top and bottom operating line intersect the diagonal at x d and x b respectively and we have to mark these points on the diagram. We will see all these points in the diagram also in the next slide. The point of intersection of two operating lines is dependent on the phase condition of the feed and so we consider the q line.

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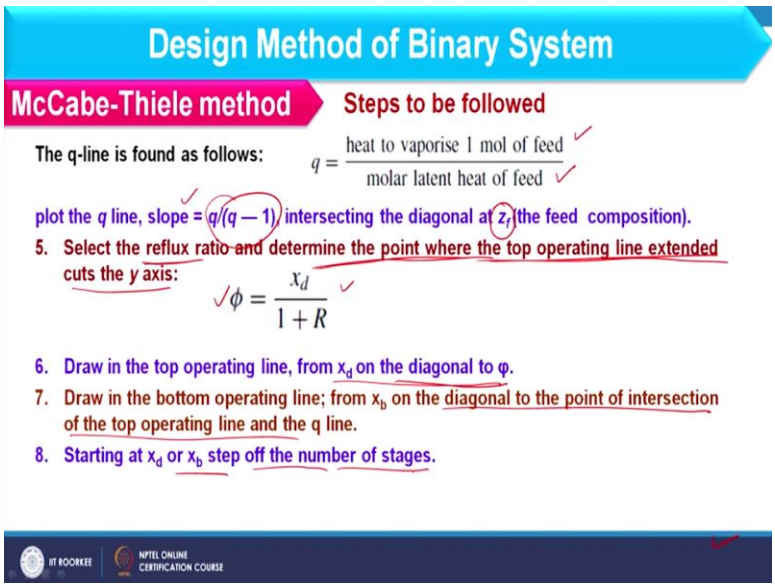

And this q line can be considered as q should be equal to heat to vapourize one mol of feed divided by molar latent heat of feed. So, we can plot the q line with the slope which is equal to q / q – 1 and intersecting the diagonal at Z f which is basically the feed composition. So, if you consider this graph here I am having the same curve that is the equilibrium curve like this and here I am having the feed condition and from this I can draw the q line.

So, that is basically the q-line and then select the reflux ratio and determine the point where top operating line extended which cuts the y axis. So, this is basically the cut on y axis and that will be equal to x d / 1 + R so we need to consider reflux ratio and then draw the top operating line from x d to diagonal of phi and draw the bottom operating line from x b to the diagonal to the point of intersection of the top operating line and the q line then starting from x d to x b step of and that should be the number of stages.

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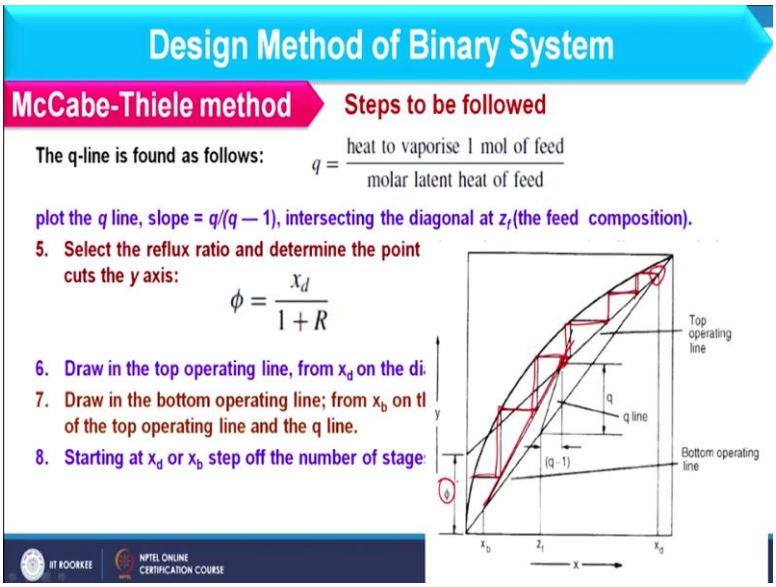

So, you can see this graph where I am having this phi value. So, this is basically the top operating value that is x d. So, from here to here you can draw the line wherever it will cut the q line from x b to that point we can draw the line and you can see from x d to x b we keep on steeping and in this way we can find the number of stages. So, in this way you can use McCabe Thiele method to find the number of stages for binary system.

For multi component system, we consider design in subsequent lectures. So, here I am stopping this lecture and we will continue the distillation column discussion with the next lecture. So, that is all for now. Thank you.