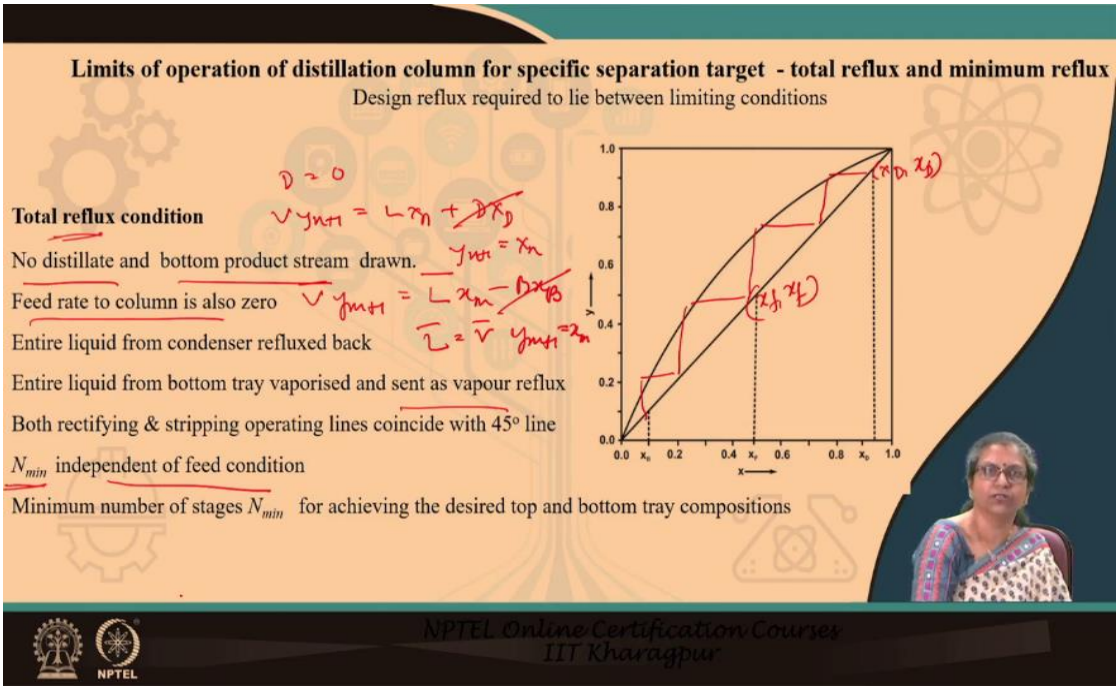
Principles and Practices of Process Equipment and Plant Design

Prof. Gargi Das
Prof. S. Ray
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Module - 02
Lecture - 13
Optimum Design

Well so, we continue with our discussions regarding the McCabe Thiele construction of the number of stages and then, we will be going over to the optimum design.

(Refer Slide Time: 00:38)



So, therefore, what we were discussing? We were discussing the limits of the separation of or rather the limits between which the reflux ratio has to operate. I had already mentioned that there are two extreme cases, one is the total reflux condition and the other is a minimum reflux condition. For the total reflux condition, we do not draw out any particular distillate. So, therefore, D is equal to 0.

Now, if you remember in the enrichment section operating line under this condition, then what do you have?

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

So, therefore, when D becomes equal to 0 naturally, then the entire vapour which had gone that same vapour is drawn. It is the same amount of liquid that is introduced as reflux into the column. So, therefore, when V=L, then $y_{n+1} = x_n$. So, therefore, we find that for such a case, for the total reflux condition, we find that the upper operating line that coincides with the diagonal line and it extends from the point (x_D, x_D) to the point (x_f, x_f).

What happens to the stripping section operating line at the same condition? For the stripping section operating line, we have the equation if you remember,

$$\bar{V} y_{m+1} = \bar{L} x_m - B x_B$$

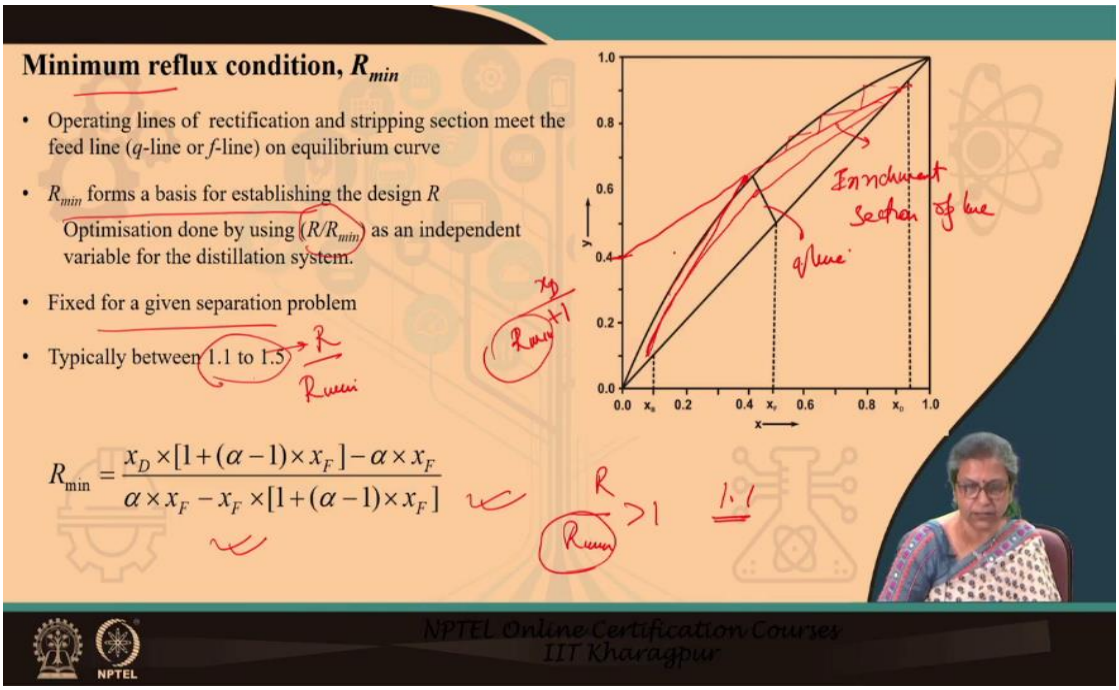
When we are not withdrawing any particular product from the top, or any particular distillate from the top naturally and we are also not withdrawing any particular bottom product, then Bx_B becomes equal to 0. In this condition, if L bar equals to V bar which says that in the stripping section also the operating line is going to coincide with the 45° diagonal line.

So, therefore, we find that under the total reflux where neither a distillate nor a bottom product stream is withdrawn. Quite naturally, the feed rate to the column is 0 under this condition. The entire liquid from the condenser is reflux back. The entire liquid from the bottom tray is vaporised and the entire vapour is sent back as the vapour reflux. Under this condition, we find that the operating lines coincide with the 45° line as I have mentioned.

In this particular case, therefore, we find that if you draw the stairs, we find that for any particular separation we, since the operating lines are furthest from the equilibrium curve so, therefore, the minimum number of stages are required to bring about any particular separation from a known feed composition.

Another important thing is that since we are not constructing the q line so, therefore, quite naturally the minimum number of the ideal stages is designated as N_{min} that is independent of the feed condition because we do not need the q-line for this particular construction. So, this corresponds to the total reflux condition.

(Refer Slide Time: 04:04)



The other thing is the minimum reflux. What happens under the minimum reflux? For the minimum reflux condition, we find that quite naturally with the minimum amount of reflux we would like to start.

So, under this condition for any particular feed condition, we will find that the minimum reflux will be achieved when the enrichment section operating line and the q-line, intersect at the equilibrium curve. Under this condition, if I am drawing the stripping section operating line and then, in that case also, we find that all of them intersect at the equilibrium curve.

So, what does this suggest? If you try to make stairs in this particular case, you find that you cannot proceed with the staircase thing. Fick says that for the minimum reflux condition quite naturally, you would require an infinite number of stages which I have already discussed.

So, for this particular condition, if you extend the enrichment section operating line to the y axis, what is the y intercept in this particular case? It is naturally $x_D/ (R_{min} + 1)$. We can write it as R_{min}, or you can write it as R_m.

So, therefore, this is the limiting operation. We cannot operate under this condition as well. But we would always like to have a reflux ratio that is higher than the R_{min}. So that the operating line shifts further away from the equilibrium curve. So, therefore, this particular case, the case from where we start from the point (x_D, x_D) and the intersection of the q-line with the enrichment section operating line that occurs at the equilibrium curve. If we intersect that part, then we find that the intersection occurs at (x_D/ R_m + 1).

So, therefore, from this construction, we can find out the R_m. Typically, it lies between 1.1 to 1.5. We know that this R_m is fixed for a given separation. As for a given separation, this x_D, x_F are all fixed, the q-line is fixed so R_m is fixed.

We can this geometrical construction. If we can write it down, we can get an analytical expression.

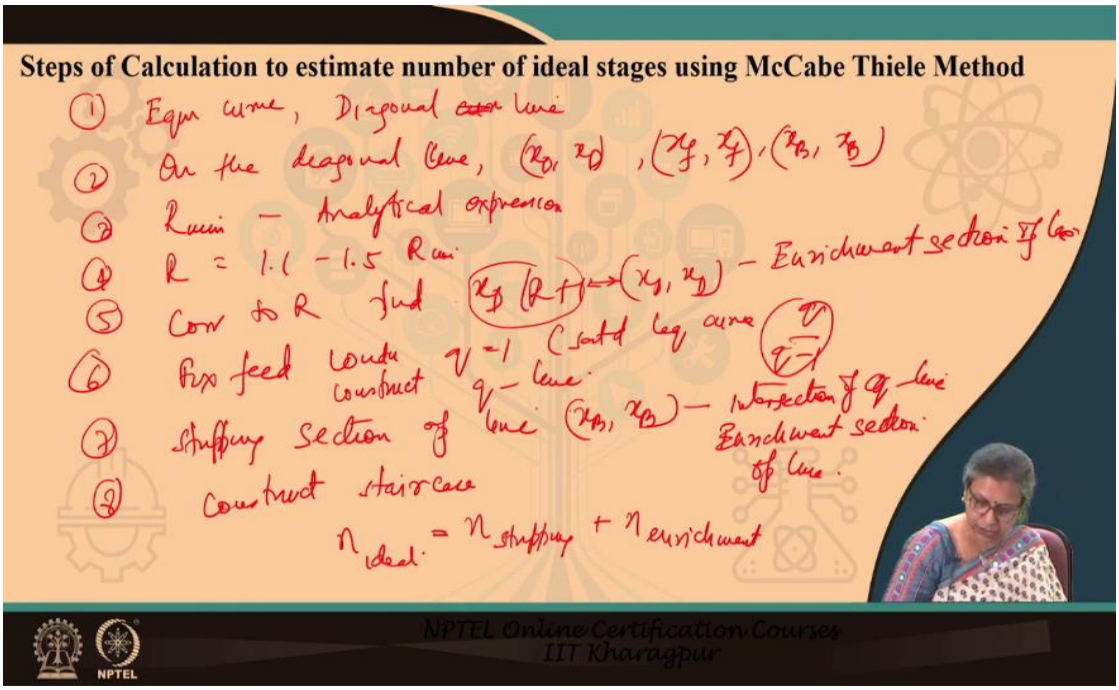
$$R_m = \frac{x_D[1 + (\alpha - 1)x_F] - \alpha x_F}{\alpha x_F - x_F[1 + (\alpha - 1)x_F]}$$

Based on this analytical expression also, we can find out R_m. Normally, what do we do? We first find out R_m for any particular design. After we have found out R_m, then we select some particular R by using R_m. So, therefore, R/R_m has to be > 1.

The R/R_m ratio typically lies between 1.1 to 1.5. So, therefore, we would always like to keep it to a little higher value such that R by any particular change in operating condition does not approach R minimum under which we will get an infeasible operation.

So, for design what do we do? We first find out the R_m for the x_D, x_F and the q point. Once we have found it out. We find out R_m either by this equation or by this particular construction. Once these are done, then we select R which is slightly higher than the R_m.

(Refer Slide Time: 08:12)



The moment, we have selected what do we do? Then, we have located the particular operating line, the actual operating line. We have located the stripping section operating line. After that, we start dropping the stairs and we find out the actual number of ideal stages corresponding to the R which is something higher than the R_m.

So, if we summarize exactly what are the different steps required for calculating ideal number of stages. The first thing is to draw the equilibrium curve and we would also locate the diagonal line. Then, on the diagonal line, we are going to locate three points mainly (x_D, x_D), (x_F, x_F), and (x_B, x_B). After that what do we do? We estimate R_m, either from the analytical expression that I have shown you or from the y-intercept from anything you can find out the R_m.

Then, we select some particular R that lies between 1.1 to 1.5 R_m. Then, corresponding to this particular R, what we do? We find $\frac{x_D}{R+1}$. Then, from $\frac{x_D}{R+1}$ on the y axis and (x_D, x_D), we draw the joining these two points. We draw the enrichment section operating line and after that, what we do?

We fix the feed condition. So, therefore, we find out to start with, I have said to start with q = 1, we assume the saturated liquid curve. Then, we find out q/(q-1). From this (x_F, x_F)

we with the slope of q/(q-1). We construct the q-line and after that, we fix the feed condition, and we construct the q-line.

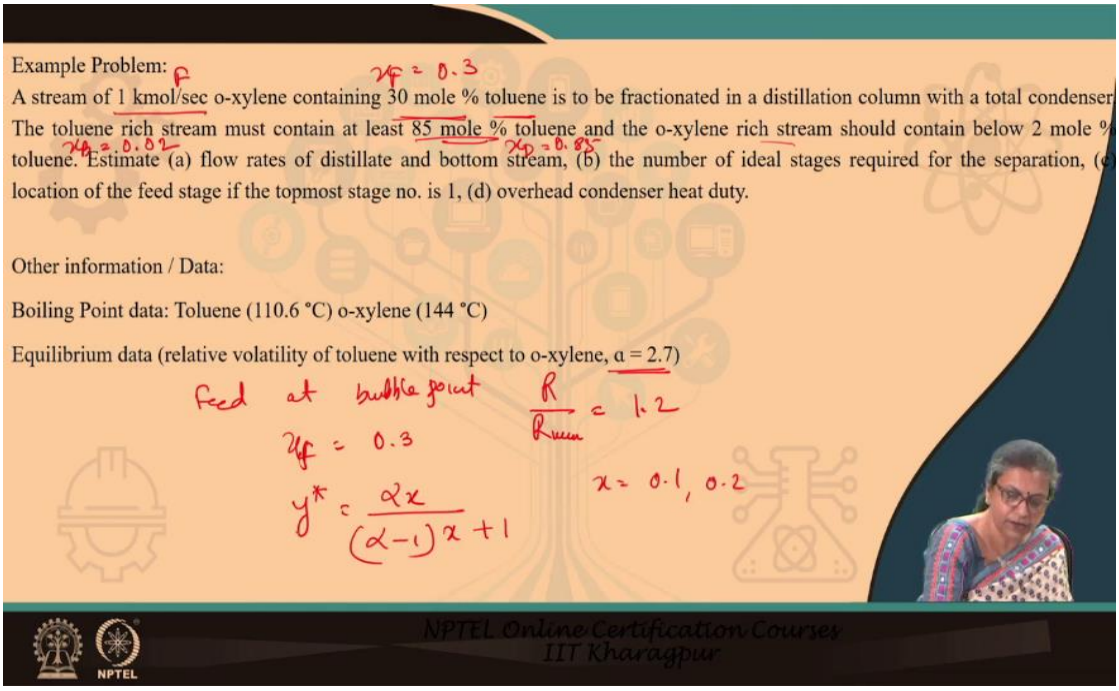
Once these two lines are drawn, then we construct the stripping section operating line. The basic assumption of the "McCabe Thiele" method is all these lines are straight lines. Therefore, the stripping section operating line starts from the point (x_B, x_B) and it intersects, it is drawn till the intersection of q-line and your enrichment section operating line.

Once this is done, then we start the staircase construction and we construct the staircase construction for the region construct staircase and for the portion before the feed or above the feed, we make the steps between the enrichment section operating line and the equilibrium curve. Beyond the q-line, we make the steps between the stripping section operating line and the equilibrium curve.

So, this is the way we do and then, we find out the $n_{stripping}$, we find out the $n_{enrichment}$ and this gives us the n_{total} number of ideal stages in this particular case.

$$n_{total} = n_{stripping} + n_{enrichment}$$

(Refer Slide Time: 12:21)



So, just to demonstrate, I have given you a problem. You can try out this problem yourself. I will just write down the steps. The steps are written following that we can do it. We find that F is equals to 1 kmol/sec, its ortho xylene which contains 30 mole% toluene, toluene is the more volatile component.

So, therefore, x_F = 0.3, we are operating with the total condenser and the toluene-rich stream means what? It is the distillate. So, the distillate composition is also given in terms of toluene.

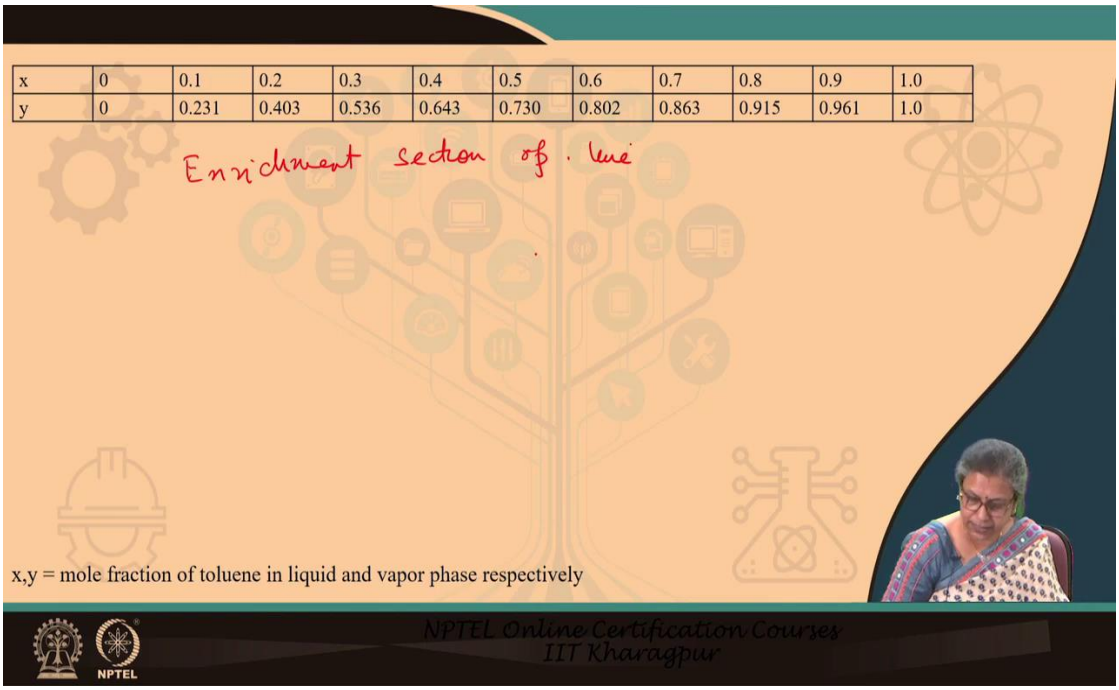
And we find that the o-xylene rich stream is what? That o-xylene rich stream is the bottom product. So, that should contain below 2 mole% toluene. So, therefore, we know x_B is equal to 0.02. So, therefore, for this particular problem initially, what do we do? We assume just every time, we assume feed is at the bubble point.

Now, I would demonstrate it or we would be working this out in this class for R/R_m = 1.2. You can try it for other R's and you can see it. x_F, it is written as 0.3, x_D I have written down 0.8, x B equals to 0.02. The alpha is given as 2.7. So, therefore, the moment the alpha is given, we know y* this is equals to we had already done it previously.

$$y^* = \frac{\alpha x}{(\alpha - 1)x + 1}$$

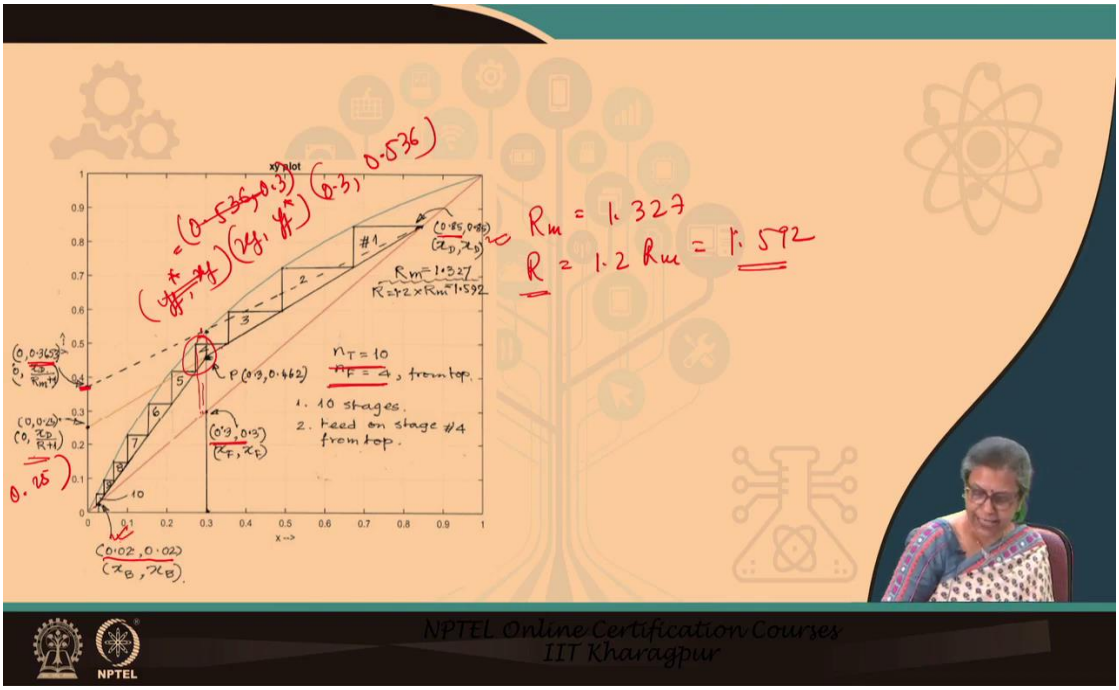
So, therefore, corresponding to x = 0.1, 0.2 etcetera we can generate the corresponding y* values and I have done it and this is tabulated in this case.

(Refer Slide Time: 14:15)



Now, we start with the enrichment section operating line. For the enrichment section operating line, what do we do? First, we need to find out the R_m.

(Refer Slide Time: 14:40)



So, therefore, for finding out the R minimum just if you can see the entire, this is the operating section line. So, therefore, it starts from (x_D, x_D) till this particular point and then, it is extended here.

So, this point is the feed point and so therefore, what is this point? You know the (x_F, x_F) point. So, therefore, this point will be corresponding to the (y_f*, x_f). You know α, you can find out y_f*. You will find that the y_f* in this particular case is equal to 0.536.

So, therefore, this particular point corresponds to 0.536. I have written it differently, it should be 0.3 and it should be written as (x_f, y_f*) which will be (0.3, 0.536). So, this point we know(feed point), this point (corresponding point on equilibrium curve) we know, we can extend it. We find when we extend it. The intercept is at 0.3653. We know x_D=0.85.

So, from there, we can find out R_m. The R_m if you find out, you will find that this corresponds to 1.327. So, we had decided that we will be working with 1.2 R_m. So, therefore, we will be working with R of 1.592.

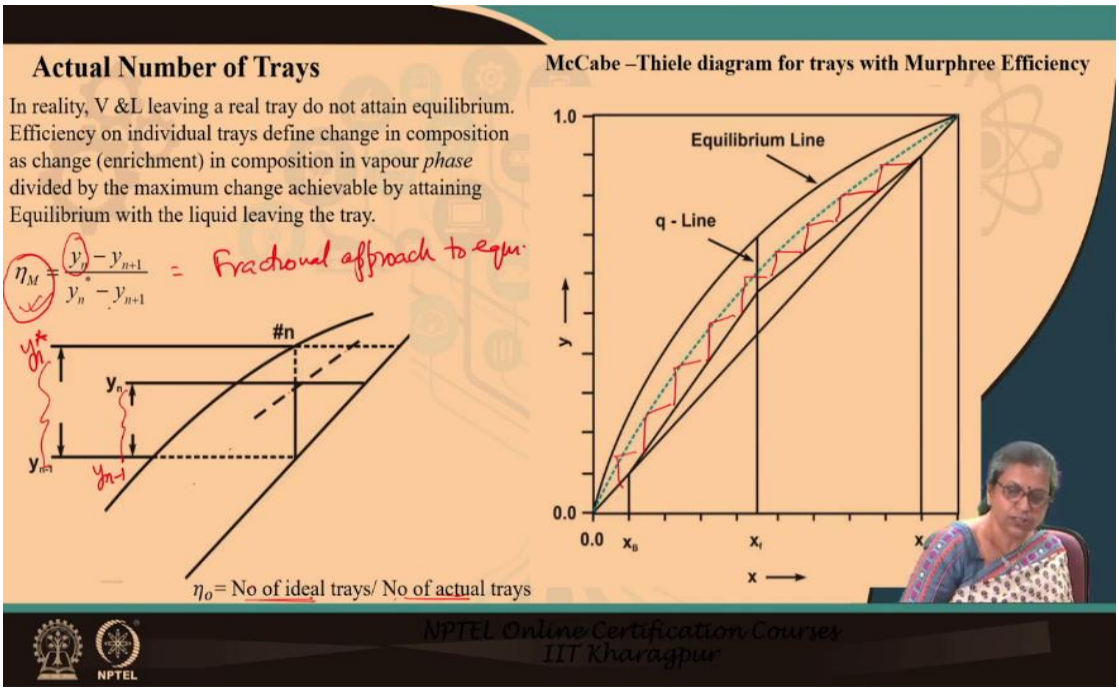
Now, for this particular case, again we start in the same way, we start with the same distillate composition and then, we extend it to the y-intercept of x_D/ (R+1). x_D = 0.85, R is equal to 1.592. So, therefore, you find that the y-intercept in this particular case, it corresponds to 0.25. So, therefore, this particular point if you observe, you find that this particular point is roughly around 0.25. So, therefore, from there, we can find out the actual R which we have already found out and more or less this line we have drawn.

Then, from the feed point what do we do? We have taken a saturated feed. We draw the vertical line and after that we know this point corresponds to the 2% toluene. There (x_B, x_B) is (0.02, 0.02). From here, we extend the stripping section operating line. Once we have done this, now we start dropping the number of steps.

Please do it yourself, you will find that in this particular process more or less, we have 3 trays specifically 3 trays in the enrichment section. In the 4th tray, we find we shift from the enrichment to the stripping section. So, therefore, it means that the feed is introduced in the 4th tray and the total number of trays are equal to the total number of stages this is equal to 10.

Try it out yourself and you are going to see that you will be getting this corresponding to a reflux ratio of 1.592 for a feed flow rate of this and a distillate recovery and the bottoms composition as specified here. Well, this is the number of ideal stages.

(Refer Slide Time: 18:40)



Now, if you remember, we had already discussed, in reality, the thing that we had assumed that the mass transfer occurs such that the steps extend from the operating line to the equilibrium curve that does not happen in practice. In practice, we find that mostly the mass transfer is much less as compared to the mass transfer under this condition. So, therefore, in reality, we find that we do not have the mass transfer to that extent rather we have a little lower mass transfer.

So, therefore, for each tray if this happens, we find that from y_{n-1} instead of going to y_n^* which lies on the equilibrium curve, actually the mass transfer happens till y_n.

$$\eta_M = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}}$$

This particular ratio is known as the Murphree tray efficiency. This gives us the fractional approach to equilibrium for each particular stage.

So, therefore, what do we do? If we know the Murphree tray efficiency, then for every point, we if we know η_M, then multiplying η_M with $(y_n^* - y_{n+1})$, we can locate y_n corresponding to each particular x. Then through all these points, we can draw the actual curve between which and the operating line, the mass transfer will take place.

We would be dropping the stairs, not between the equilibrium and the operating line, but between the line that we have drawn and the two operating lines and from here. We find that quite naturally the number of actual stages, which are required, will be much higher as compared to the number of stages that will be required for the ideal stages.

Now, this is one particular definition of tray efficiency. There is another way also by which we define the overall tray efficiency and which defines as the number of ideal trays which are required for any particular separation divided by the actual number of trays that are required to bring about this particular separation.

(Refer Slide Time: 21:19)

Conservative overall efficiency η_o (%) for typical industrial columns

Process	Service	Enrichment section	Stripping section
Amine absorber	DEA or MDEA	-	50
Regenerator column for amine absorption system	Sour gas - DEA	-	10
	Sour gas - MEA or MDEA	-	15
Sour water stripper	Water-H_2S	-	25-35
Solvents	Hexane / Heptane	75	80
Light hydrocarbon separation	De-methanizer/De-ethanizer	100	100
	Ethylene fractionator	95	95
	De-propanizer	90	75
	Propylene-propane fractionator	95	90
	Debuanizer/naphtha stabilizer	90	75
Aromatic separation	Benzene column	70	70
	Toluene column	65	60
	Xylene column	80	80
	C8 – C9 splitter	80	70
Others	Ethanol - water	60	60
	Isopropanol - water	70	70

η_o complex function of
- Geometry & design of contacting trays
- Flow rates & flow paths of V/L streams
- Composition & properties of V/L streams

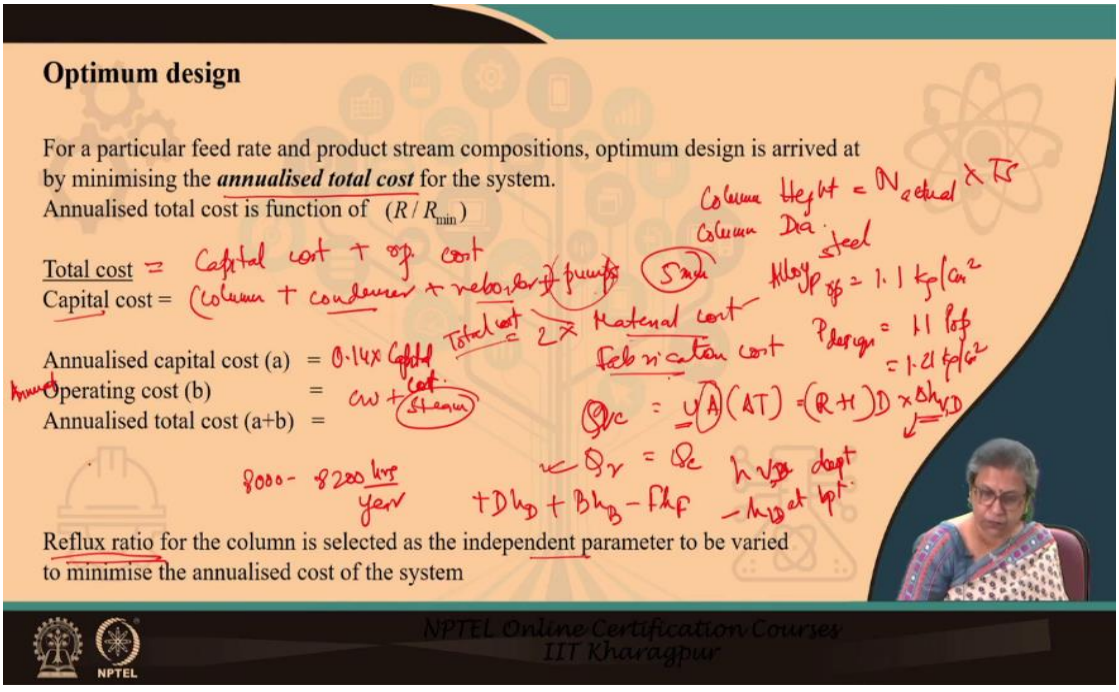
Mostly, we use this overall tray efficiency in finding out the actual number of stages or the actual number of trays. Normally, we find that this overall efficiency is a complex function. Like the geometry design of contacting trays, the flow rates, the flow paths, composition, and properties of the vapour-liquid streams etc.

Typically, from the available industry data, I have noted down a few particular processes and the corresponding η_o, the overall tray efficiencies for the enrichment section and the stripping section. This can be referred to while you would like to find out the actual number of trays.

For example, in your particular case, we found that you were operating an o-xylene column. For the o-xylene column, the efficiency in the enrichment and the stripping sections can be taken as 80.

So, therefore, you have found out the number of trays in the enrichment section, you have found out the number of trays in the stripping section. For each particular case, you are supposed to find the actual number of trays in the enrichment section which is nothing, but the ideal number of stages divided by 0.8. The same thing you are supposed to do for the stripping section. In this case, also, n ideal divided by 0.8, from adding up these two. You would get the actual number of trays in the total column that you require well.

(Refer Slide Time: 22:59)



So, the entire thing, what I had discussed, is at one particular reflux ratio. Now, normally, what you are supposed to do? Normally, we would like to go for an optimum design. As I have already discussed that for the optimum design, we would like to use optimum R.

Optimum rather we would like to find out the optimized design based on that particular reflux flow rate which would give us the minimum annualized total cost as I have told you.

So, therefore, we select the reflux ratio for the column as the independent parameter to minimize the annualized cost.

Now, what is this annualized cost? First, let us see what is the total cost. The total cost is equal to the equipment cost or you can say the capital cost plus the operating cost.

$$total\ cost = capital\ cost + operating\ cost$$

What are the things which should be included in the capital cost? Capital cost naturally should include the cost of the column, the cost of the condenser, the cost of the reboiler, and also the cost of the pumps. Normally, these costs are much higher. So, therefore, we normally do not include this. This does not contribute much to the cost.

Now, for all these things, there are two things; one is a material cost will be there, the other will be a fabrication cost. Normally, what do we do? We can find out the material cost. How you would like to find out the material cost? You know what is the material that you will be using may be for the column. For this particular column, we would go for alloy steel. Then, for this particular column, we know that what is going to be the column height. The column height can be obtained from the number of trays as well as the tray spacing which I will be discussing shortly after this.

So, therefore, once I know the total column height which where I know that the column height is nothing, but the number of trays, the actual number of trays into the tray spacing.

$$column\ height = N_{actual} \times Tray\ spacing$$

We have to find out the column diameter. After that, we can find out the thickness of the shell. The details regarding the thickness of the shell will be discussed in the discussions or when we discuss the pressure vessels. Usually, the shell thickness is taken as 5 mm. It is not less than 5 mm. The thickness is based on the operating pressure.

Normally, as I have said the P_{op} is equal to 1.1 kg/cm^2. The P_{design} is taken as 1.1 times the P_{op} which gives this as 1.21 1 kg/cm^2. So, from here, the shell thickness can be obtained. From the shell thickness etc., we can find out the material cost. Usually, the fabrication

cost and the material cost are taken as equal. So, therefore, for the column, the material cost into 2 gives us the total cost of the column.

$$Total\ Cost\ of\ the\ column = material\ cost \times 2$$

Same way for the reboiler and the condenser, what are they? They are nothing, they are simply the two heat exchangers. So, therefore, if we can find out the Qc, if we can find out Qr the heat loads, then we know that Qc is equal to UAΔT. Qr is the same.

$$Q_c\ or\ Q_r = UA\Delta T$$

So, therefore, if we know the overall heat transfer coefficient, we would be in a position to find out the area. Once we have found out the area, then we can go for the cost data.

Now, we are not going into the details of the entire cost, you will not be asked to do the detailed calculation. But the concepts which had been discussed will be asked during your assessment questions and the final exam as well.

So, therefore, the condenser and the reboiler costs can also be obtained in this particular way. We know that the Qc is nothing but equals to the total amount of heat load. The detail mathematical expression is as follows:

$$Q_c = (R+1)D \times \Delta h_{vap}$$

$$\Delta h_{vap} = h_{V,D|dew\ point} + h_{L,D|bubble\ point}$$

So, therefore, from Δh_{vap}, we can find out the latent heat of vaporization. From Q_c the expression, we can find out the Qc.

Normally, for the Qr what do we do? We know the Qc, we know that the total enthalpy, which is going out with the distillate, we know the total enthalpy which is going out with the bottoms product, and we know that the total enthalpy which has entered with the feed so, from these enthalpy calculations, we can find out Qr.

$$Q_r = Dh_D + Bh_B - Fh_F$$

So, therefore, we can find out the total cost which is nothing but equal to the capital cost plus operating cost. Capital cost I have already discussed, operating cost among the

operating costs what do you have? You have got the cost of steam as well as the cost of the cooling water.

So, therefore, if you know what is the amount of steam or the amount of cooling water that you require, you know the price and you can assume. For a continuous plant, you can assume say 8000 to 8200 hr per year of operation in 1 year. So, therefore, you can find out the annual operating cost.

Now, for the capital cost, you have found out the total capital cost, it comes from the material cost as and to you can double it by 2 so that you can get the entire total cost including the material cost, fabrication cost. We do not include the cost of transportation etc.

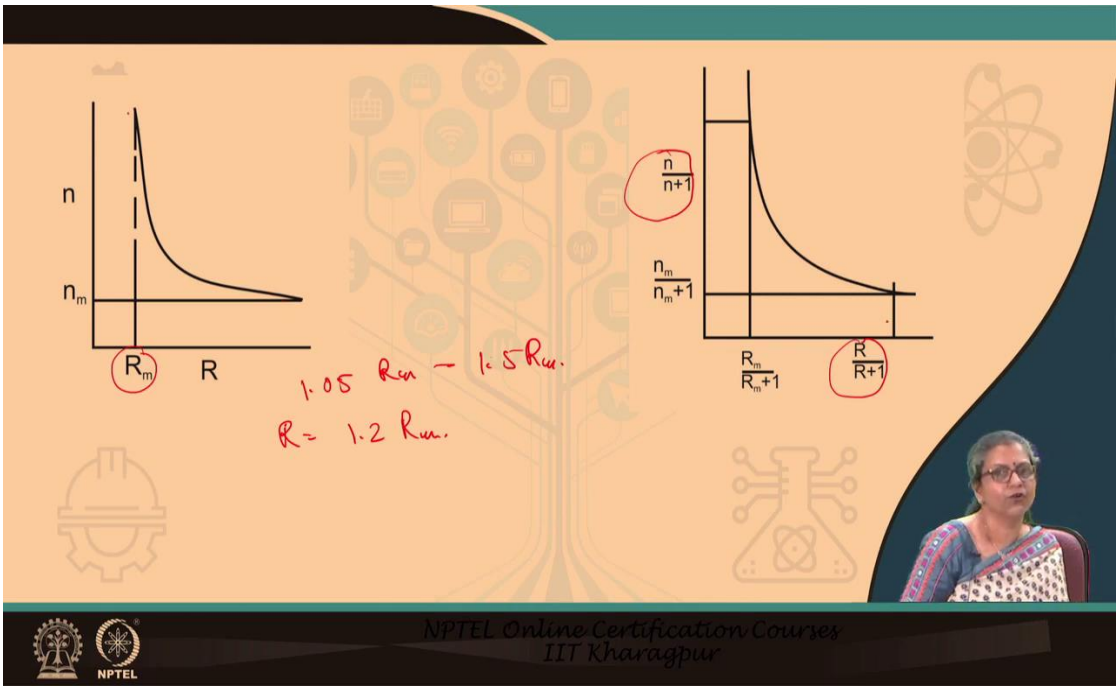
Now, this total cost from where you get? You either have to take a bank loan and then in that case depending upon the loan rate more or less loan rate is between 12 to 14 %. So, therefore, the annualized capital cost is nothing, but 0.14 into the capital cost.

This is the bank interest rate that you have to pay if you have taken a bank loan. If you have not taken a bank loan, you have got the money, you are investing, then in that case the loss of interest that you are incurring because you have not kept in the bank and you are investing here.

So, therefore, once you find out the capital cost, you can find out the annualized capital cost, you can find the annual operating cost based on the total amount of consumption of cooling water as well as your steam. Usually, the steam cost is much more as compared to cooling water cost. Once you have found this out, you can find out the annualized total cost by adding the two, and then for each reflux ratio, you can generate this.

$$annualized\ total\ cost = annualized\ capital\ cost + annualized\ operating\ cost$$

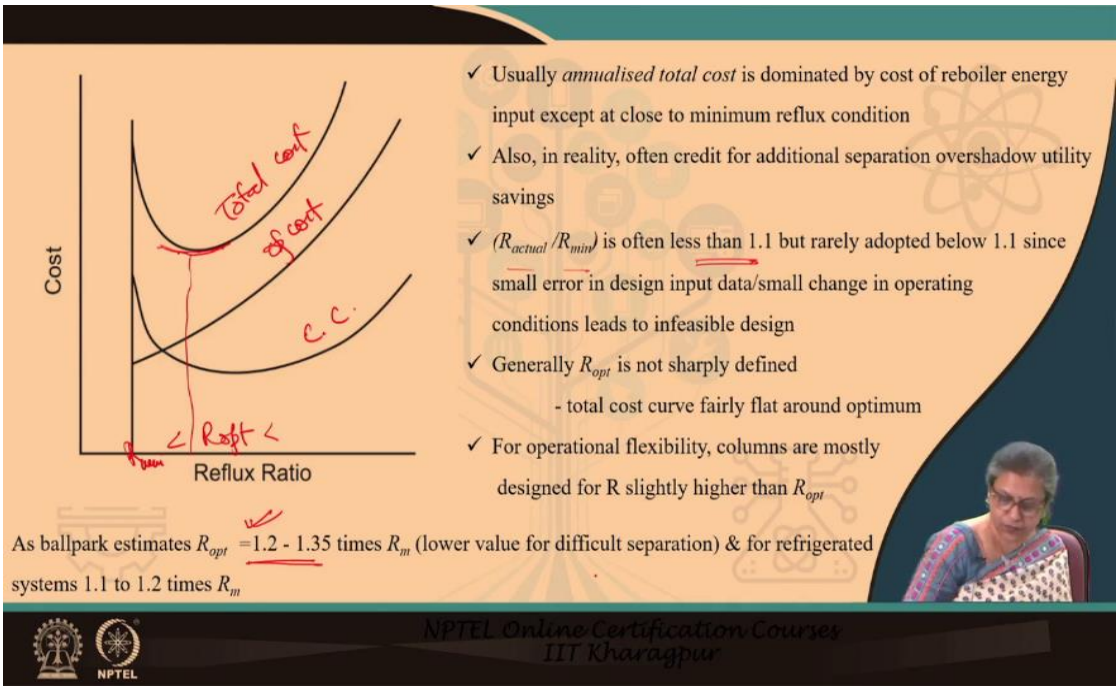
(Refer Slide Time: 30:55)



Normally, we find that with an increase in reflux ratio as you know that for a very low reflux ratio at R_m, the number of trays goes to infinity. Then, it falls and it is asymptotic in this particular way. In order to fix the limits at the two ends, generally we plot n/(n+1) as a function of R/(R+1) and the graph can be generated.

The problem that I had given you, you can try it out, I had done it just for R equals to 1.2 R_m. You can extend it, you can start from 1.05 R_m to 1.5 R_m. For each particular R_m, you can generate the n. The n/(n+1) and you can generate the curve and see for yourself what you are going to get.

(Refer Slide Time: 31:49)

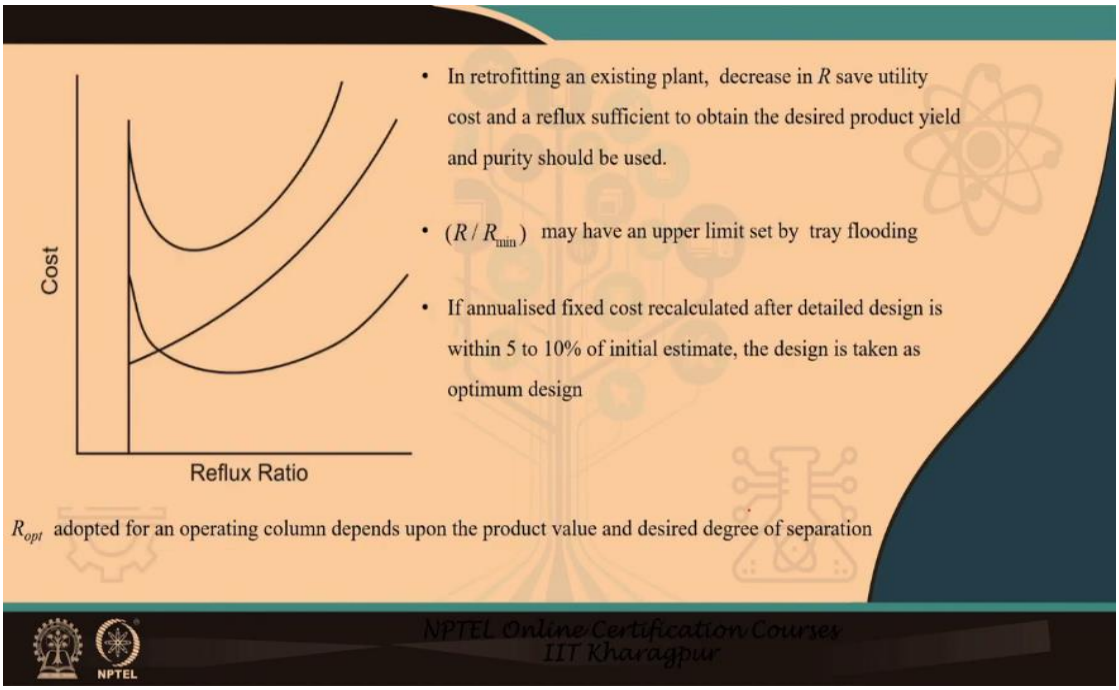


After that, if all the details of the cost can be obtained, then definitely (I have already discussed that the cost versus reflux ratio) this gives you the capital cost. This gives you the operating cost from where we can get the total cost. Normally from the total cost, we can locate the $R_{optimum}$ value. For this R optimum, it lies between the R_m and definitely, the total reflux is infinity. So, therefore, R_{opt} is always greater than R_m.

So, therefore, this R_{opt} is located, this is obtained from economics. We find that in practice, R_m can be less than 1.1, but we rarely adopt that. Mostly, we find that this particular flattened portion extends for quite some time. So, therefore, we can take up any value of R and we can operate it.

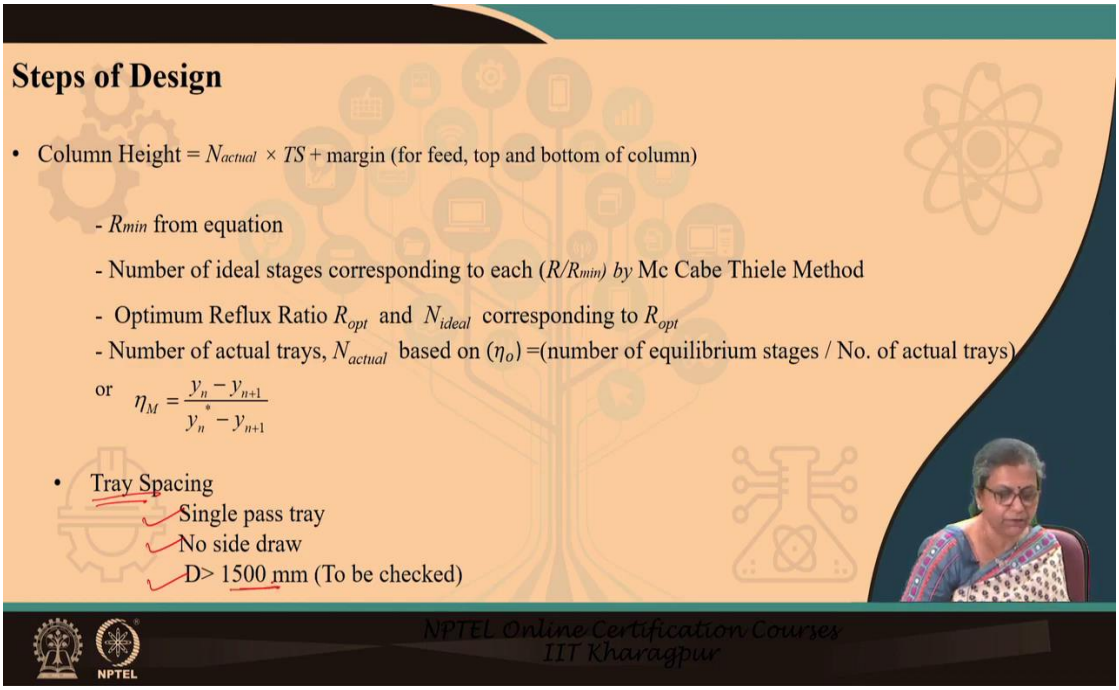
Normally, it is taken, you can assume that R_{opt} will lie between 1.2 to 1.35 times of R_m, this value is quite naturally for more difficult separations and this is for the easier say easier separations.

(Refer Slide Time: 33:08)



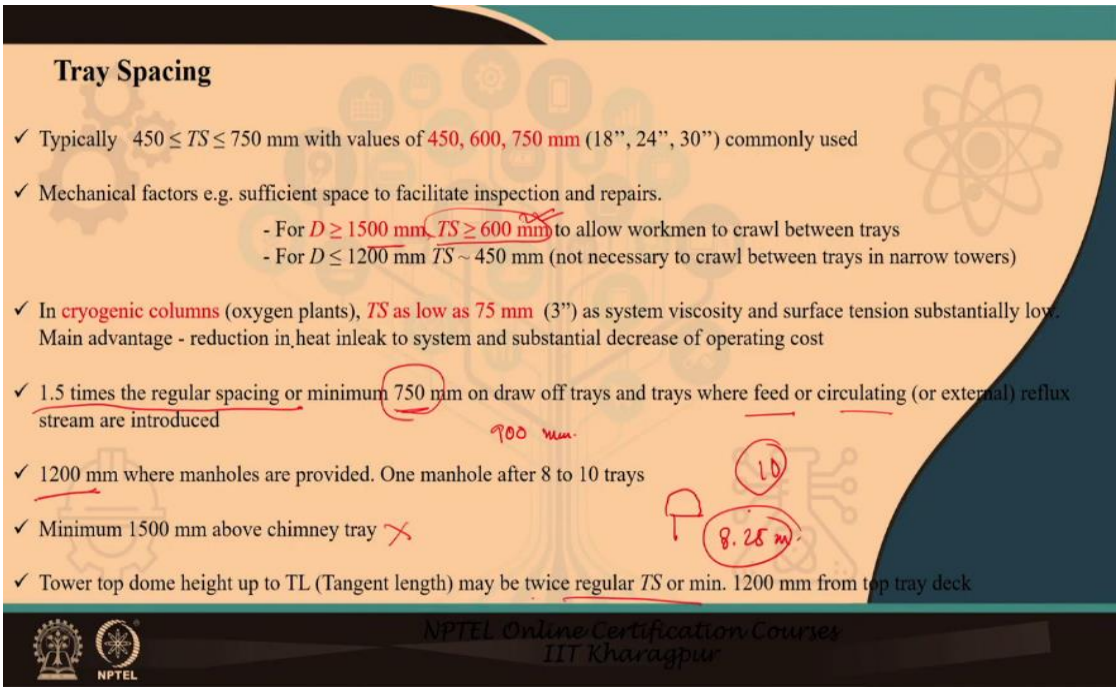
Now, once you have calculated the whole thing, after that the entire cost has been done based on certain assumptions.

(Refer Slide Time: 33:23)



What are the assumptions that we had taken? The assumptions 1, where we had taken a single pass tray, we did not assume any side draw and then, for finding out the tray spacing. Usually to start with we assume that the diameter of the column is greater than 1500 mm.

(Refer Slide Time: 33:39)



Then, typically to find out the column height, we know the number of actual stages. We would also like to find out the tray spacing so that from these we can find out the column height.

So, for tray spacing, certain thumb rules are there which will be discussed in greater details when we go for the column internals. For now, it is sufficient for you to remember that usually for diameters greater than 1500 mm we can assume a tray spacing of 600 mm.

Normally, the diameter that you are going to get for your vapour flow rate for which you are going to opt for a tray tower will be > 1500 mm. So, to start with, you can take up this particular tray spacing and with this particular tray spacing, you can find out the column height.

Now, this is the normal tray spacing for different trays. Now, remember one thing that tray spacing will be different for a feed tray, you need additional space as I had said to allow for vapour disengagement so that liquid is not entrained. So, normally, we find that for

feed trays for circulating reflux streams etc., it is either 1.5 times the regular spacing which is a minimum of 750 mm.

Remember one thing for trays, we require manholes through which a person can enter and fit the trays or if any repair or anything is required the person can enter. So, therefore, whenever manholes are provided, you an additional tray space is required. You do not have a chimney tray for the moment in your problem so, you need not bother about this.

Then, after the top tray the dome which you have that particular dome, it is usually twice the regular tray spacing. So, for your particular column that you had in that column, we found out that there were 10 trays. Now, remember one thing out of these 10 trays, 1 goes to the reboiler. So, therefore, actually in the column how many trays you have? You have got 9 trays.

Now, among these 9 trays, 1 was the feed tray. So, above the feed tray, you need 750 mm spacing. Below the bottom tray, you would require, I forgot to mention below the bottom tray also, you would be requiring around 900 mm of spacing.

So, therefore, for the remaining number of trays, you can assume 600 mm of spacing. For the bottom-downcomer, you can assume 750 mm or 900 mm. For the feed tray, you can assume 750 mm.

Since there are 10 trays, 1 tray will be provided with a manhole for that you can assume 1200 mm and then you find out the total column height. It will come to something around I just check it up it will be around 8.25 meters. So, from there, you can find out the column height.

Now, for the cost along with column height, you also require to find out the column diameter. Regarding the column diameter, there are some standard techniques that we are going to discuss, when we are going to discuss the column internals part.

So, once you know the column diameter, then you know the column height, then you can find out the column cost, you can find out the reboiler and the condenser cost from everything you can find out the capital cost, you can also find out the operating cost, total cost. Repeat this particular calculation for different reflux ratios, generate this curve. Find

out the optimum reflux ratio and then, you can proceed to find out the actual number of stages for an optimized design.

So, this completes the discussion on distillation columns distilling binary components. In the next class, we will be discussing multi-component distillation and how we deal with those particular situations.

Thank you very much.