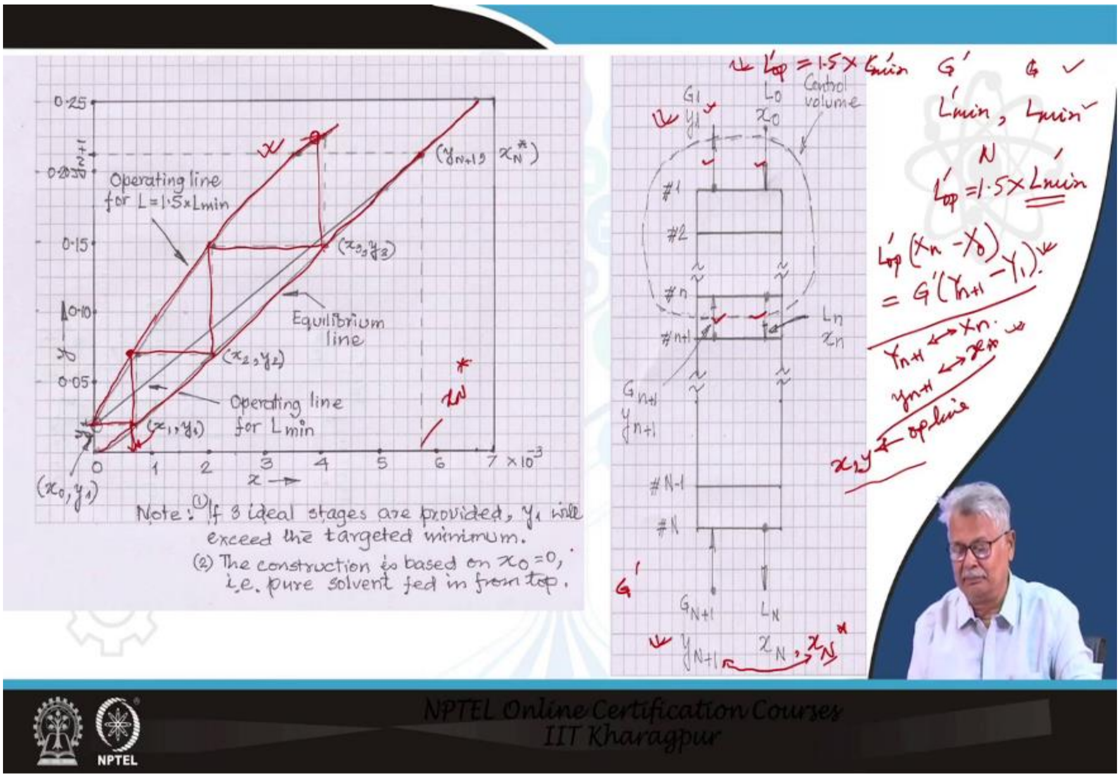
Principles and Practices of Process Equipment and Plant Design
Prof. S. Ray
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Module - 02
Lecture - 19
Design of absorbers (Contd.)

(Refer Slide Time: 00:39)



Note: ① If 3 ideal stages are provided, y_1 will exceed the targeted minimum.
② The construction is based on $x_0 = 0$, i.e. pure solvent fed in from top.

$L'_{op} = 1.5 \times L'_{min}$ G' G ✓

L'_{min}, L_{min} ✓

N ✓

$L'_{op} = 1.5 \times \underline{\underline{L_{min}}}$

$L'_{op}(X_n - X_0) = G'(Y_{n+1} - Y_1)$

$Y_{n+1} \leftrightarrow X_n$

$y_{n+1} \leftrightarrow x^*$

$x, y \leftarrow$ op line

Hello, wish you all a good day. So, we continue with our Design of an absorber session. To start with we have a very little a very short recapitulation of what we talked about in the last class. This is a figure which you had seen and where we had found out two things.

We had found out L'_{min}, we found out G' where these two are the solute free flow rates in mol/(kmol-h) or something like that. We definitely have the corresponding total mole of flow rates as G and L rather this should be L_{min}.

But, we understand that this varies along the column. Naturally, L_{min} will also vary along the column that is the liquid flow rate across the individual ideal stages. Here, we have capital N number of ideal stages as shown and as we have talked about earlier.

We have found and we have told you how to draw the operating line. The operating line has to be drawn with a particular L_{op} which is typically around 1.5 times L_{min}. Now, what we have done is we also have told you that how to determine this L_{min}, because under this L_{min} condition this particular concentration is x_N^* which is in equilibrium with the corresponding y_{N+1}.

Here, we have a small x, small i, and small y which are the mole fraction coordinates. We have the equilibrium line here, the equilibrium line goes like this. This is the data we have collected from literature and this is the starting point and this is the end-point here. So, this end-point concentration naturally will, in this time when we have L'_{min} as the flow rate of the solvent, this is definitely your x_N^* which is in equilibrium with y_{N+1} that is what we have told right now.

We also have derived an equation of the operating line. The operating line starts here and it keeps on going and it grows here like this. Now, in the operating line how is the operating line based? The operating line equation is based on simply the mass balance along the, around this envelope. What do you have here? We have said if my L'_{min} is a flow rate of my solute free solvent, it starts with a concentration of x_0 and goes to a concentration of x_n.

So, naturally, this is the increase in change in concentration. So, that is the pickup of my solute which also has to match the pickup of my solute from the gas phase. The gas-phase enters with a composition of y_{n+1} and whatever goes out is with a composition of y_1. So, this basically is x_n.

Now, in a general sense what we have is a relationship between Y_{n+1} and X_n. We know that on a mole fraction basis the corresponding values are y_{n+1} and x_n. So, the same relationship could also be written in terms of the small y and the small x and it could be generalized.

In the last session, the slide that we have given a generalized equation which relates this y and x and this y and x are the concentration of the components of vapour and the liquid here that their concentrations. Now, what we do is we have a very similar procedure, that top end of the column is having a composition of (x_0, y_1).

We know these are the parameters known to us already. We know the inlet concentration Y_{n+1}, the exit concentration Y_1 because that is the task, the amount of solute that has to be removed and after removal, the concentration has to come to Y_1. We also know the flow rate G', now we are going to do this for a flow rate of L'_{op}which is nothing, but about 1.5 times L'_{min}. We know L'_{min}. So, L'_{op} is also known for us.

So, we start drawing this operating line based on this $L'_{op} = 1.5 \times L'_{min}$. Now, we have a relationship between x and y this is the operating line equation. This will be more clear when we deal with an example with specific numerical values.

Now, if I assume an x, I can always calculate the value of y and we know what is the minimum value of x. The minimum value of x is x_0 and what is the maximum value of x that corresponds to x_N^*. So, we vary x from x_0 to x_N^* which is in equilibrium which we have just found out as well. We find out the corresponding values of y and we plot it here as an operating line.

This end on the operating line tells us that this is the corresponding composition here and here. So, naturally the coordinate of this point will be x_0 and y_1. Now, what we also know that if we move here what we have? We have to correspond to y_1 the corresponding components of the liquid phase. So, this basically has got the composition x_1 and what we do is, this particular thing if i go up we will find another operating point in the next stage and we keep on moving like this.

This I did not say in details. But what we feel here is obvious that the procedure is exactly the same as the McCabe Thiele construction that you have done in the case of the binary distillation and the procedure is all is absolutely the same. Here I just like to add one more thing that in this specific case of an absorber, this construction looks like this and all these triangles that we make are above the equilibrium line.

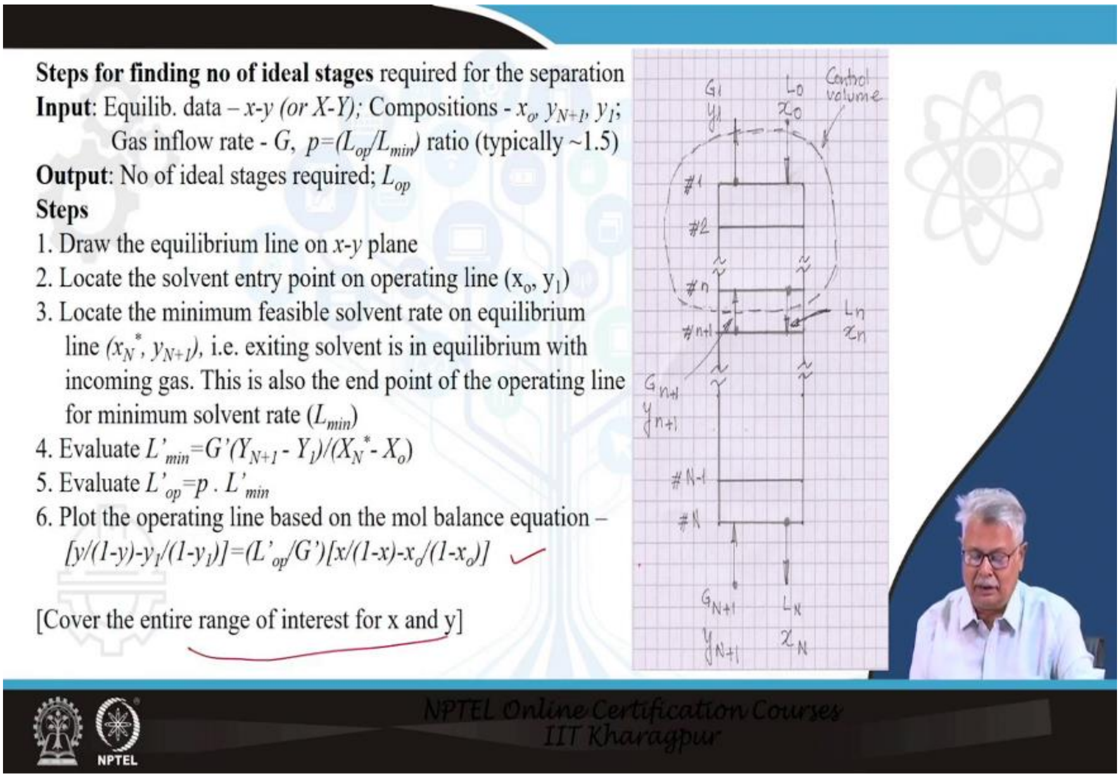
In the case of stripping, the operating line falls below the equilibrium line and such triangular constructions are constructed below the equilibrium line, but the procedure is the same. With this in brief we have found that after 1, 2, 3 after the third stage what we have is we have exceeded Y_{n+1}.

What is the physical significance? That means, if I have instead of Y_{n+1}, a higher value which corresponds to the ordinate of this, even then we will be reaching the value of Y_1

under this operating condition with L'_{op}. So, this is a safe design which is a very small amount of margin also.

If you want to be exact we will only say that we really do not require three stages. We do not require four stages. We require about 3.8. So, with this, we will move on and this is how you find out.

(Refer Slide Time: 09:33)



Steps for finding no of ideal stages required for the separation

Input: Equilib. data – x-y (or X-Y); Compositions - x_o, y_{N+1}, y_1;
Gas inflow rate - G, $p=(L_{op}/L_{min})$ ratio (typically ~1.5)

Output: No of ideal stages required; L_{op}

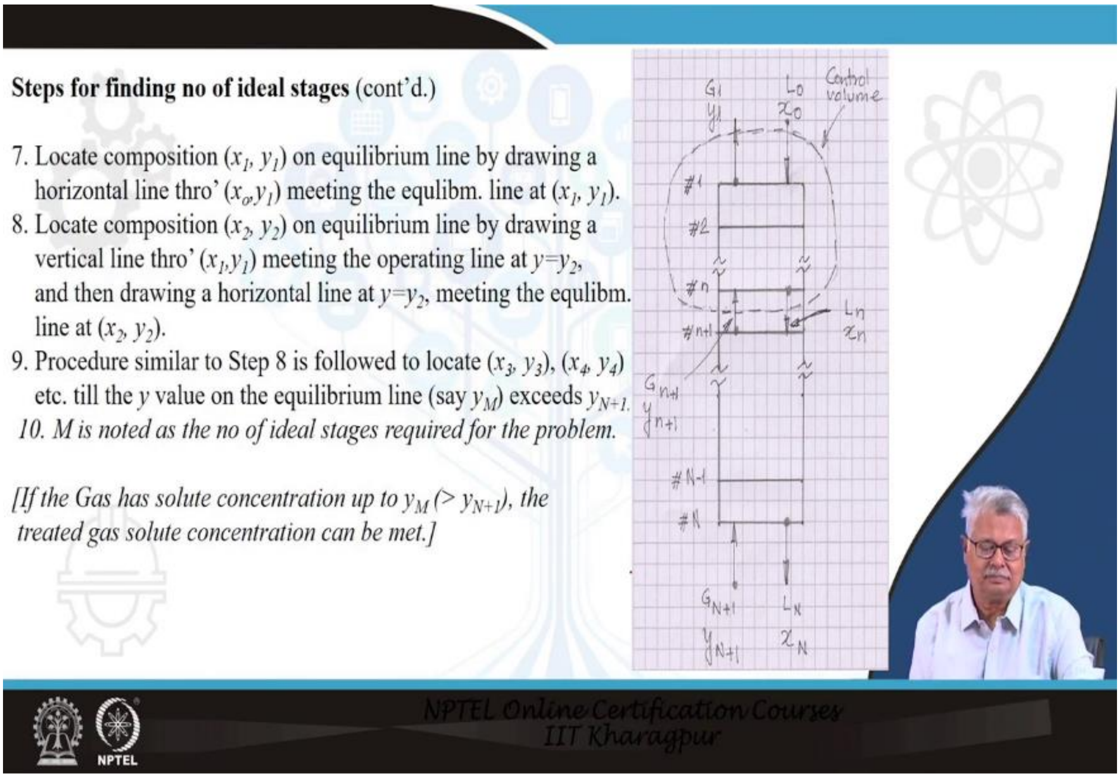
Steps

1. Draw the equilibrium line on x-y plane
2. Locate the solvent entry point on operating line (x_o, y_1)
3. Locate the minimum feasible solvent rate on equilibrium line (x_N^*, y_{N+1}), i.e. exiting solvent is in equilibrium with incoming gas. This is also the end point of the operating line for minimum solvent rate (L_{min})
4. Evaluate $L'_{min}=G'(Y_{N+1}-Y_1)/(X_N^*-X_o)$
5. Evaluate $L'_{op}=p\,.\,L'_{min}$
6. Plot the operating line based on the mol balance equation – $[y/(1-y)-y_1/(1-y_1)]=(L'_{op}/G')[x/(1-x)-x_o/(1-x_o)]$

[Cover the entire range of interest for x and y]

Here the same thing is written stepwise in a set of instructions. What we have is basically how to plot the operating line and it has to cover the entire range of interest for x and y for x naturally its x_0 to your x_N^*.

(Refer Slide Time: 09:55)



Steps for finding no of ideal stages (cont'd.)

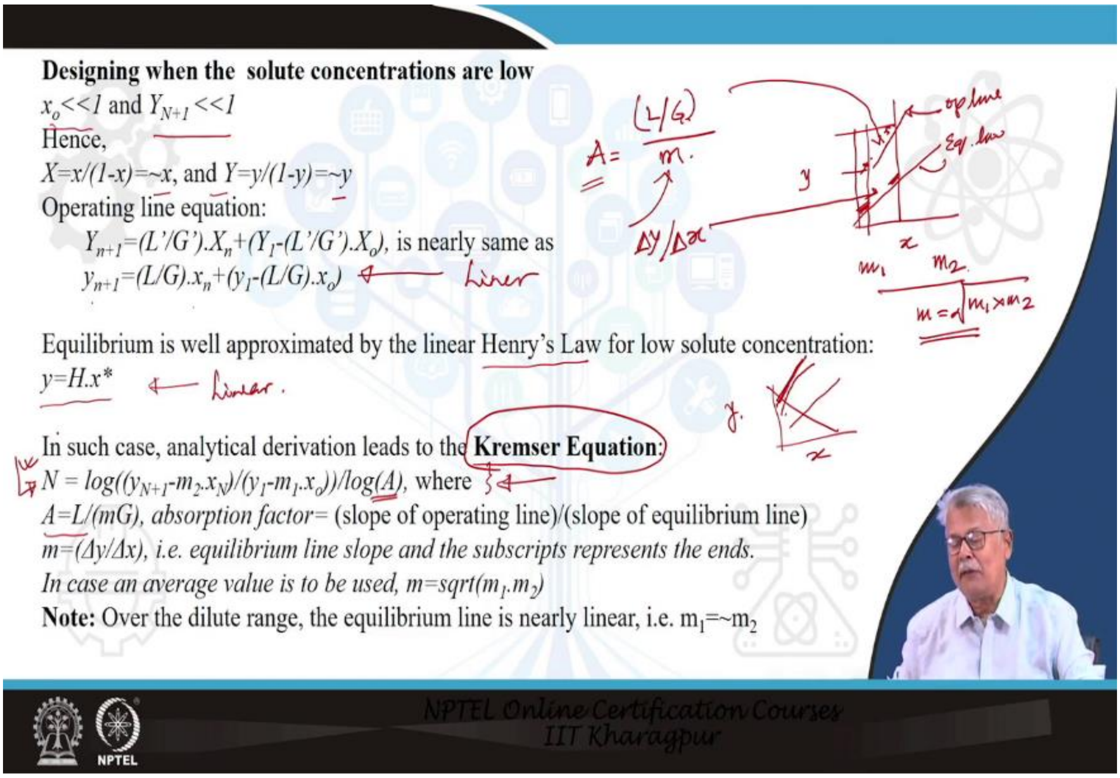
7. Locate composition (x_1, y_1) on equilibrium line by drawing a horizontal line thro' (x_o, y_1) meeting the equlibm. line at (x_1, y_1).
8. Locate composition (x_2, y_2) on equilibrium line by drawing a vertical line thro' (x_1, y_1) meeting the operating line at $y=y_2$, and then drawing a horizontal line at $y=y_2$, meeting the equlibm. line at (x_2, y_2).
9. Procedure similar to Step 8 is followed to locate (x_3, y_3), (x_4, y_4) etc. till the y value on the equilibrium line (say y_M) exceeds y_{N+1}.
10. *M is noted as the no of ideal stages required for the problem.*

[If the Gas has solute concentration up to y_M ($> y_{N+1}$), the treated gas solute concentration can be met.]

NPTEL Online Certification Courses
IIT Kharagpur

This exactly is a procedure for finding out the number of stages required which we already have demonstrated.

(Refer Slide Time: 10:07)



Designing when the solute concentrations are low

$x_o << 1$ and $Y_{N+1} << 1$

Hence,

$X = x/(1-x) = \sim x$, and $Y = y/(1-y) = \sim y$

Operating line equation:

$Y_{n+1} = (L'/G').X_n + (Y_1 - (L'/G').X_o)$, is nearly same as

$y_{n+1} = (L/G).x_n + (y_1 - (L/G).x_o)$

Equilibrium is well approximated by the linear Henry's Law for low solute concentration:

$y = H.x^*$

In such case, analytical derivation leads to the **Kremser Equation**:

$N = \log((y_{N+1} - m_2.x_N)/(y_1 - m_1.x_o))/\log(A)$, where

A=L/(mG), absorption factor= (slope of operating line)/(slope of equilibrium line)

m=(Δy/Δx), i.e. equilibrium line slope and the subscripts represents the ends.

In case an average value is to be used, m=sqrt(m₁.m₂)

Note: Over the dilute range, the equilibrium line is nearly linear, i.e. $m_1 = \sim m_2$

NPTEL Online Certification Courses
IIT Kharagpur

Now, we have another case, the case that we have dealt with so far a little bit higher concentration of the solute in both the phases. Now if, when we know that when my concentrations are small; that means, my x_0 is very small Y_{N+1} is also very small. That means that both the inlet concentration of solute in the liquid and the vapour phase are small in that case capital X and small x and capital Y and y are almost the same.

So, the operating line equation is approximately this.

$$y_{n+1} = (L/G)x_n + (y_1 - (L/G)x_0)$$

So, what we have here is a simplified expression for the operating line equation. We also know and what we find here, this is a relationship between y and x and it is linear that is a major thing and we know that under dilute solutions with low concentration Henry's law is valid for most of the systems.

$$\text{Henry's Law: } y = Hx^*$$

Where H is naturally Henry’s law constant and this is also a linear equation. Now, when I say this, we can derive an analytical expression for the number of stages required. Now, this analytical expression involves one thing.

This is x, this is y and this is basically your y is equal to H x which is equilibrium line and here what you have is your operating line.

Now, when you have to go from x_0 to x_n or the value of y has to go from here to here the numerical number of, it can be numerically in fact, it can be geometrically found out or rather its nothing, but having an analytical expression for this particular geometry, that how many numbers of steps are required to go from one particular point from this point to this point.

So, what we find here is the expression is this and this is called the Kremser equation. It is a very famous equation which is based on the linearity of the equilibrium line as well as the operating line.

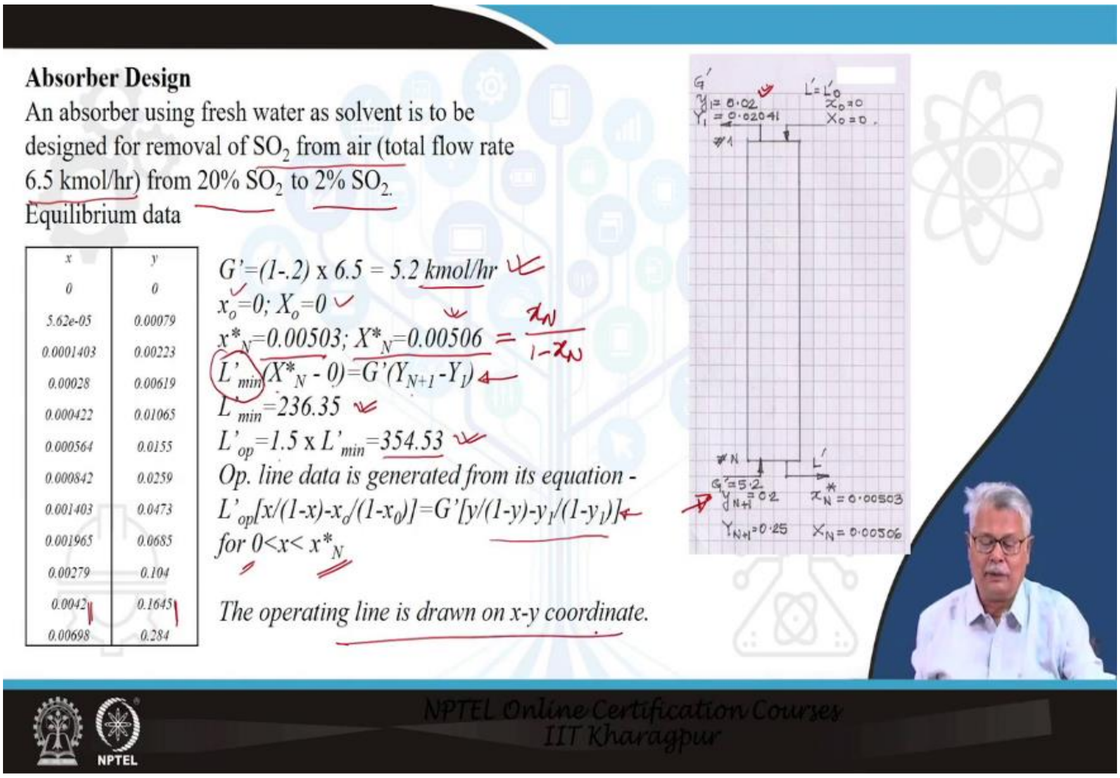
$$N = \log((y_{N+1} - m_2 x_N)/(y_1 - m_1 x_0)) \,/\, \log(A)$$

Now, there is something else. This involves a constant a which is known as the absorption factor. What is this absorption factor? It is written here L/mG which is also the same as L/G divided by small m and what is the small m? The small m is the $\Delta y/\Delta x$ for the equilibrium line and what is L by G? This is basically the slope of the operation line. So, this absorption factor is the slope is the ratio of the slope of the operating line to the equilibrium line both are linear. So, all through the range of concentration change, it remains constant.

Now, if you are talking to if you are trying to handle x situation in which the equilibrium line is slightly curved. So, you may have one slope here and another slope here. One slope is m_1 the other end the slope is m_2 in that case, you use the square root value of (m_1*m_2) and it has been found that it also gives pretty good estimation of the m.

Now, remember one thing the Kremser equation is primarily used for dilute solutions and quite naturally we will see that in the diagram that we have there our operating line is rather curved, but the equilibrium line is fairly linear. So, even if we try to use Kremser equation and that over there, we will find that it will be giving us an approximate value of the number of stages.

(Refer Slide Time: 14:48)



Absorber Design

An absorber using fresh water as solvent is to be designed for removal of SO_2 from air (total flow rate 6.5 kmol/hr) from 20% SO_2 to 2% SO_2.

Equilibrium data

x	y
0	0
5.62e-05	0.00079
0.0001403	0.00223
0.00028	0.00619
0.000422	0.01065
0.000564	0.0155
0.000842	0.0259
0.001403	0.0473
0.001965	0.0685
0.00279	0.104
0.0042	0.1645
0.00698	0.284

$G' = (1-.2) \times 6.5 = 5.2$ kmol/hr

$x_0 = 0;\ X_0 = 0$

$x^*_N = 0.00503;\ X^*_N = 0.00506 = \frac{x_N}{1-x_N}$

$L'_{min}(X^*_N - 0) = G'(Y_{N+1} - Y_1)$

$L'_{min} = 236.35$

$L'_{op} = 1.5 \times L'_{min} = 354.53$

Op. line data is generated from its equation -

$L'_{op}[x/(1-x) - x_0/(1-x_0)] = G'[y/(1-y) - y_1/(1-y_1)]$

for $0 < x < x^*_N$

The operating line is drawn on x-y coordinate.

We have a case of an absorber design example with us. The absorber is using freshwater as a solvent for the removal of SO_2 from the air, the total flow rate of the air is 6.5 kmol/h and it has got 20% SO_2. So, quite naturally 20% of SO_2 is 1.3 kmol/h SO_2 and the rest amount is inert air and it is brought down to 2 % SO_2.

We find out G' which is the solute free gas flow rate and which remains constant all through. We are going to use freshwater. So, naturally, mole fraction of SO_2 in my water that comes in x_0 and corresponding x_0 is also 0.

Now, we look at the equilibrium data which is available here. It is in mole fraction directly corresponding to this particular y_{N+1} is equal to 0.2 which is approximately somewhere in between these two, we find out that by interpolation the corresponding x_N* value is 0.00503.

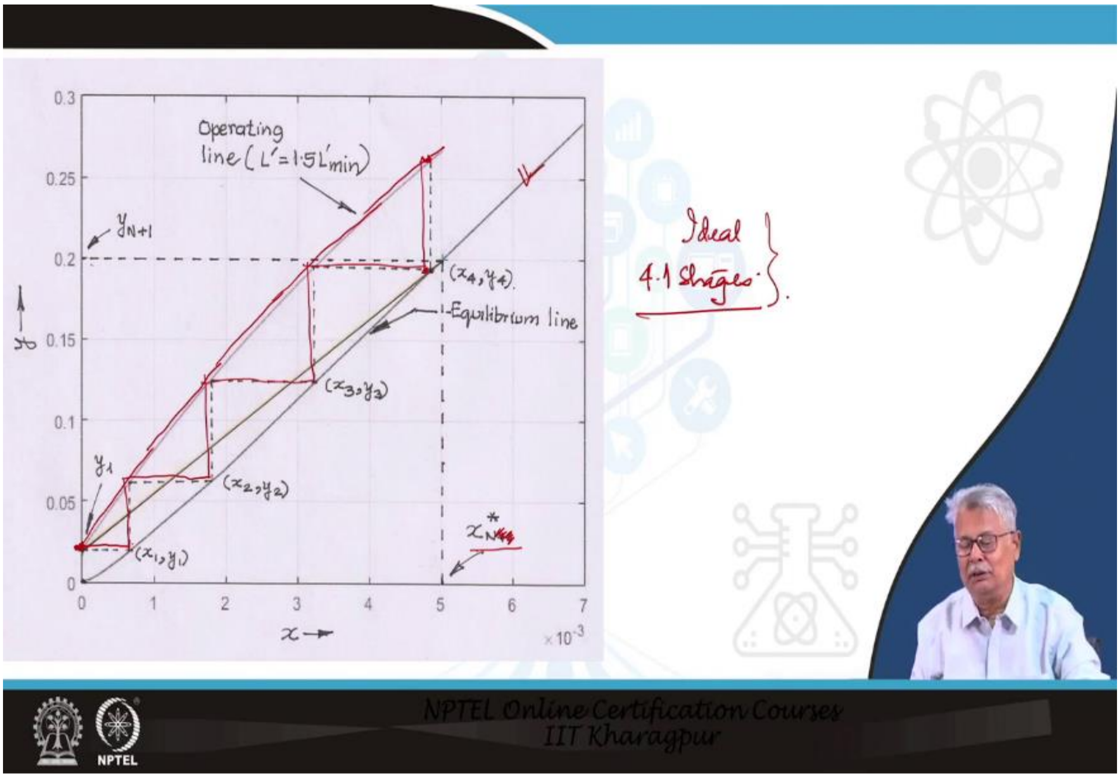
Now, the equilibrium concentration and mole fraction and we in solute free basis we find this as simply $x_N/(1- x_N)$. So, that is how we get this value which is the solitary basis. We write the overall mass balance equation to find out my L'_{min}.

The change in concentration of L' is basically from 0 to x_N^* and in the case of G', it changes from y_{N+1} to y_1. So, based on this we find out that my L'_{min} is 236.35 kmol/h.

What do we consider now? We consider that my operating L' is going to be 1.5 times the L'_{min} and we get here simply 236.35 multiplied by 1.5 gives me 354.53. Now, we write the operating line equation here and we know my range of interest in x will start from 0 and the maximum value can be x_N^*.

So, what we do is if we take different values of x, I can find out the other values of the corresponding y and plot the operating line on the x y coordinate we have done just that.

(Refer Slide Time: 17:35)



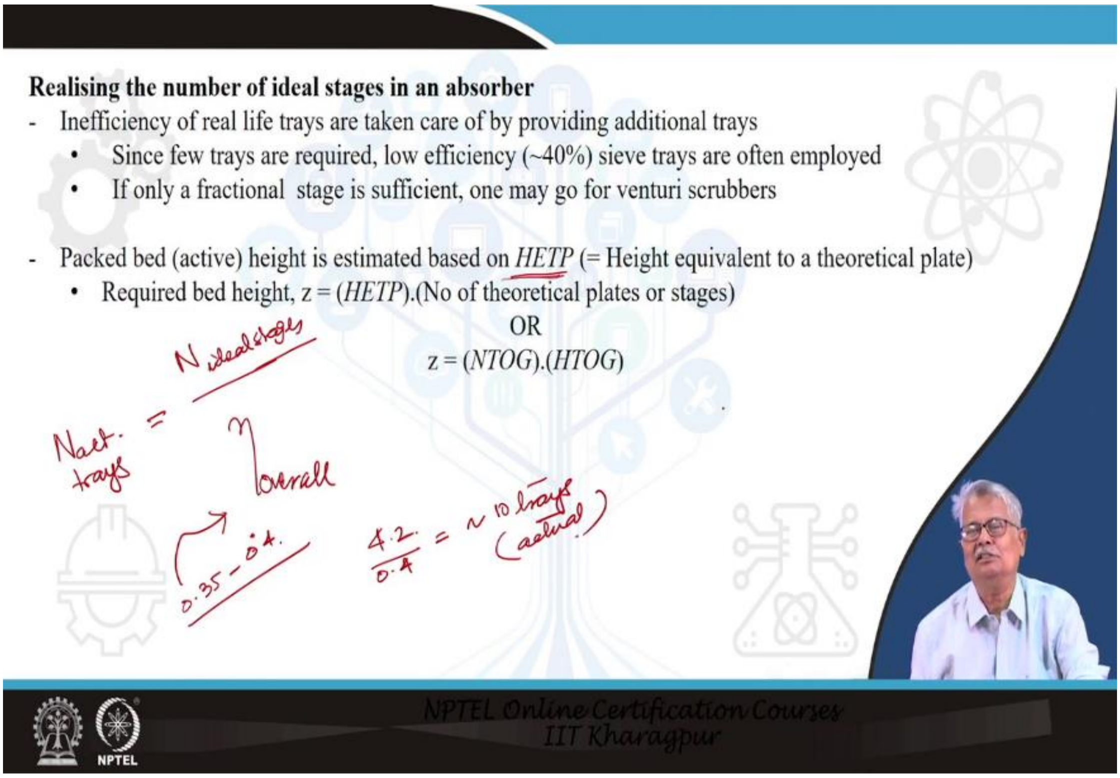
Here what we have is a x y coordinate here we have is the y and here we have the x, the equilibrium data is here. The corresponding to the L'_{min} is my starting point which is the top of my absorber and this is the bottom end and we have noted that corresponding to y_{N+1}. What we have here is basically x_N^*.

So, we find out here in this particular case the operating line exactly the way I have said is drawn here, we make the first step by touching the equilibrium line going upcoming to the horizontal again touching it going up at these points correspond to the compositions (x_1, y_1) and (x_2, y_2) and this I keep on repeating.

You will notice one thing. In this specific case, how many stages we have considered? We have considered 1, 2, 3 and 4 and in the fifth stage if I go, the fifth stage is gives me or allows me to have instead of 0.2 possibly something around 0.26 constant inlet concentration and instead ideally if I can find out if I can really provide 4.1 stages, we will be too happy to do it.

So, basically what we find here that we require 4.1 ideal stages here or we can say that we require slightly more than 4. So, this is the way you find out the number of ideal stages in this specific design problem if you want you can repeat the calculation yourself.

(Refer Slide Time: 19:50)



Realising the number of ideal stages in an absorber

- Inefficiency of real life trays are taken care of by providing additional trays
  - Since few trays are required, low efficiency (~40%) sieve trays are often employed
  - If only a fractional stage is sufficient, one may go for venturi scrubbers
- Packed bed (active) height is estimated based on *HETP* (= Height equivalent to a theoretical plate)
  - Required bed height, z = (*HETP*).(No of theoretical plates or stages)

OR

z = (*NTOG*).(*HTOG*)

$$N_{\text{act. trays}} = \frac{N_{\text{ideal stages}}}{\eta_{\text{overall}}}$$

$0.35 - 0.4$

$$\frac{4.2}{0.4} = \sim 10 \text{ trays (actual)}$$

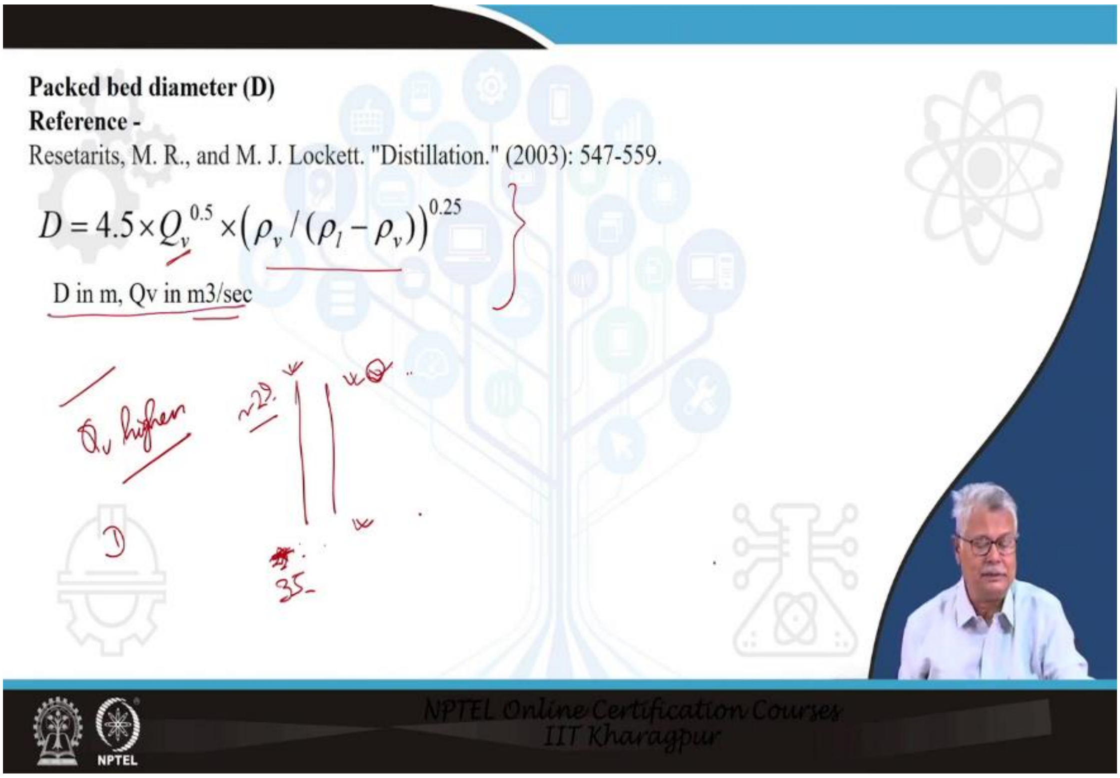
Now, comes the main problem. Realising the number of ideal stages in an absorber. We have found the ideal number of stages, but the trays are only 100 % efficient. So, naturally if you are going to provide a tray tower and I know its overall efficiency, the number of actual trays is equal to the number of ideal stages divided by the efficiency in fraction.

Typically, if you are going to use a sieve tray, possibly you will have an efficiency value of 0.35 to around 0.4. So, quite naturally if I am having 4.2 divided by and I consider the efficiency of around 0.4. So, you understand it will be around 10 trays actual. Now, we talk about the other consideration that is you don't have to be going to use absorber, where you are going to use trays.

You are going to use a packed tower there let us see how you find it out. In that particular case, we know height equivalent to a theoretical plate. Height equivalent to a theoretical plate it what does it mean? It means basically what exactly is the depth of packing required to provide one ideal stage of contact.

We know 4.2 in this particular case has been the total number of ideal stages. So, what we could say here in this particular case my depth of packing should be 4.2 times HETP. Now remember this already has the cushion of HETP because the height of the real packing, i.e. the active packing length for the transfer.

(Refer Slide Time: 22:00)



Packed bed diameter (D)
Reference -
Resetarits, M. R., and M. J. Lockett. "Distillation." (2003): 547-559.

$$D = 4.5 \times Q_v^{0.5} \times \left(\rho_v / (\rho_l - \rho_v)\right)^{0.25}$$

D in m, Qv in m3/sec

Now, there is something here. Height equivalent to a theoretical plate is basically a theoretical rather it is a practical estimate. Normally, packing vendors will be telling you how to estimate this HETP and what exactly is the correlation to be used. HETP has to be a function of the mass transfer coefficient, the packing size, the flow rates and the mass transfer itself.

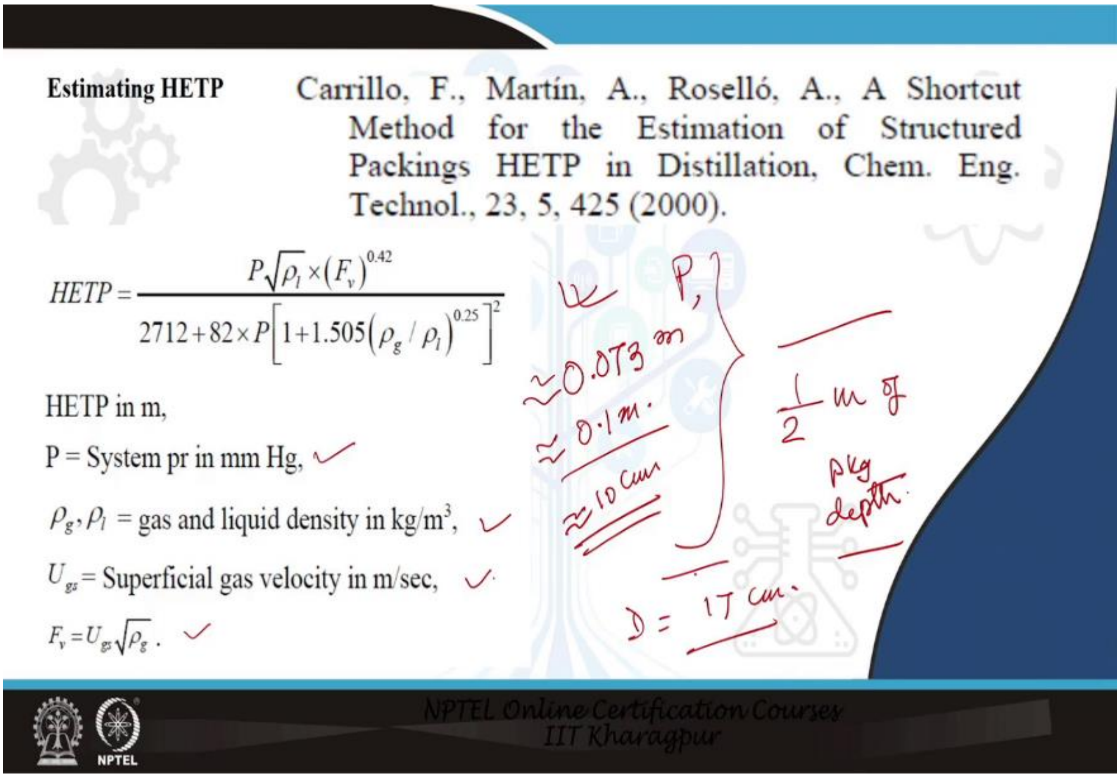
Now, we are still solving the same problem. What do we have? We have a reference here that gives us an idea that how to estimate a tower diameter in case of a packed bed what we have here is, D equals 4.5 into the flow rate of the vapour in m^3/S multiplied by a dimensionless factor.

$$D = 4.5 \times Q_v^{0.5} \times \left(\rho_v/(\rho_l - \rho_v)\right)^{0.25}$$

If I do this to find out Q_v, we need to find out the condition at the top, at the bottom. It is obvious that at the bottom you have the number of moles more in the vapour phase, but at the top usually, your Q_v will be higher. So, normally you will be evaluating the Q_v at the top and the bottom and you will be taking the Q_v of the higher value.

Now, based on this you will be finding out the diameter, you will also note one thing. Your Q_v is basically in this specific particular case what happens the molecular weight initially is 35, and as it goes up to its close to 29. So, the number of moles here will be slightly more and that gives you a normally slightly higher Q_v. Now, after you have estimated this it's time for you to estimate the HETP.

(Refer Slide Time: 24:17)



Estimating HETP

Carrillo, F., Martín, A., Roselló, A., A Shortcut Method for the Estimation of Structured Packings HETP in Distillation, Chem. Eng. Technol., 23, 5, 425 (2000).

$$HETP = \frac{P\sqrt{\rho_l} \times (F_v)^{0.42}}{2712 + 82 \times P\left[1 + 1.505(\rho_g/\rho_l)^{0.25}\right]^2}$$

HETP in m,

P = System pr in mm Hg, ✓

ρ_g, ρ_l = gas and liquid density in kg/m³, ✓

U_{gs} = Superficial gas velocity in m/sec, ✓

$F_v = U_{gs}\sqrt{\rho_g}$. ✓

P, ?

≈0.073 m

≈0.1 m.

≈10 cm

$\frac{1}{2}$ m of pkg depth.

D = 17 cm.

NPTEL Online Certification Courses
IIT Kharagpur

HETP is found from various correlations, but for vapour-liquid contacting there is a simplified method which is published in 2000 and it goes like this, it involves a pressure of the column it is for a low-pressure column. P is a system pressure in millimetre mercury, ρ_g and ρ_l are gas and liquid density in kg per meter cube, U_{gs} is a superficial gas velocity in m/s and F_v is $U_{gs}\sqrt{\rho_g}$.

In this expression, what you find is after all if you evaluate your problem with these known conditions at the top and the bottom you will find there are two differences in HETP. But the differences are not high. I have already calculated this using this particular data here and we get a very small value of HETP and this comes typically close to around 0.073 meters say 0.1 meter which makes it around 10 cm.

You will notice one thing. It is a system in which you have a sufficient difference in the density you also have a sufficiently low viscosity also. That means you are expected to have a good mass transfer coefficient and based on that the generalized correlation gives us 10 cm of packing depth and with around 4.2 stages it will be about 42 cm of depth, roughly I will round it off to about 500 mm or I will be using half meter of active packing depth.

If you look at the value of the D itself, the value of the D itself is also not much. What you have is basically a much smaller value and your D comes to approximately 17cm, there is a thumb rule. Sometimes it is said that the HETP is close to the diameter value. Here we have a diameter of around 17cm and we have an HETP estimate to be around 10 cm we find that this particular thing is also fairly ok and this thumb rule is also often used.

I think with this I have given you a gross overview of the absorption in the three classes that we have concluded and what I intend to do right now after this is, we will think of real towers and the tower internals for mass transfer and we are expecting to focus primarily on the vapour liquid contacting towers. To start with we will see what are the different tower types and how they are to be chosen.

Thank you. Thank you all for today.