Mass Transfer Operations I

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Module - 4
Absorption
Lecture - 2
Packed Tower Design Part 1

Welcome to the second lecture of module four which is on absorption. Before going to the second lecture, let us have a small recap of the previous lecture we had.

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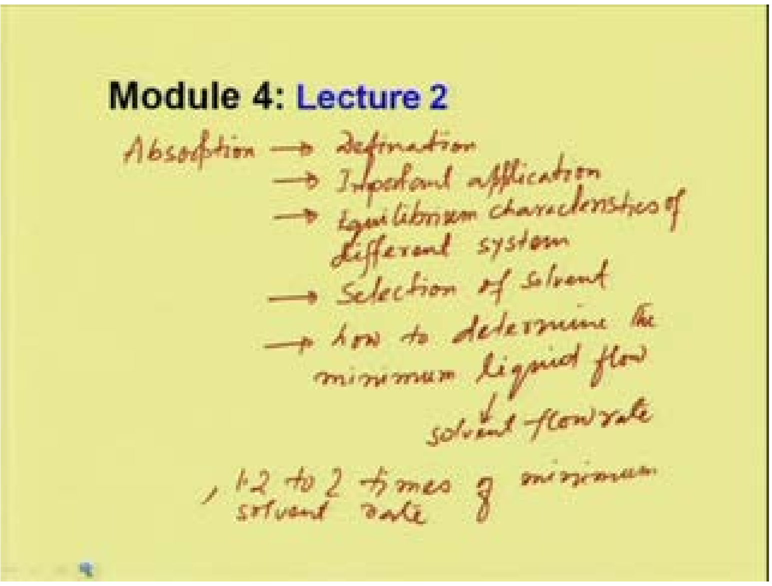

Module 4: Lecture 2

Absorption → defination
→ Important application
→ equilibrium characteristics of different system
→ Selection of solvent
→ how to determine the minimum liquid flow
↓
solvent flow rate

, 1.2 to 2 times of minimum solvent rate

In our previous lecture, we just had an introduction why absorption is important, it is definition important application, and then we discussed the equilibrium characteristics of different system. Then the selection of the solvents and the other think which is how to determine how to determine the minimum liquid flow rate liquid flow rate, liquid or solvent, in other words solvent flow rate. And then we have given an example how to determine the minimum liquid flow rate, and in general the solvent circulation or flow rate is about 1.2 to 2 times of the minimum solvent rate. So in this lecture, we will start the design of packed towers.

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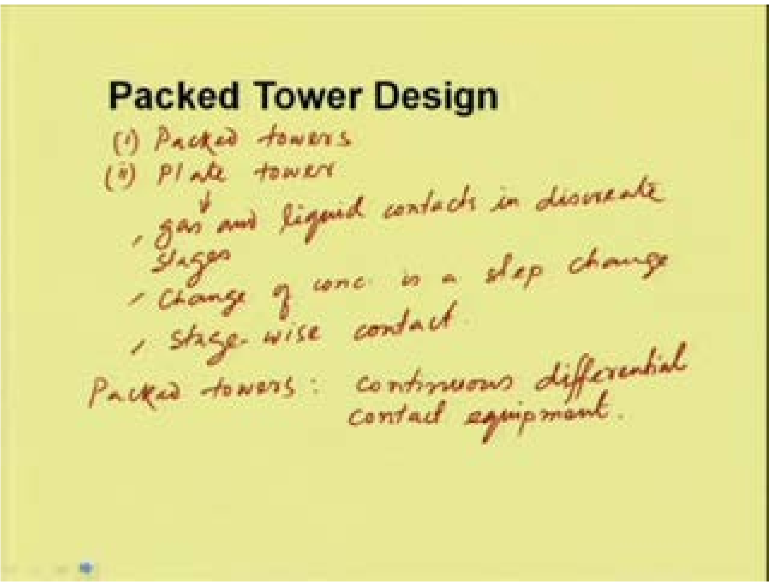

Packed Tower Design

(i) Packed towers
(ii) Plate tower
↓
/ gas and liquid contacts in discreate stages
/ change of conc in a step change
/ stage wise contact

Packed towers : continuous differential contact equipment.

The conventional equipment for absorption studies are the two equipment, one is the packed towers and second one is the plate tower. In plate towers the gas and liquid contacts in discreate stages, and the change of concentration change of concentration is a step change and this contactor plate column tower is known as the stage wise contact, stage wise contact. On the other hand, if we consider packed towers, in this case the gas and liquid they come in contact, in a continues contact between the gas and the liquid over the packing materials throughout out the column, so we call this packed towers as the continuous differential contact equipment.

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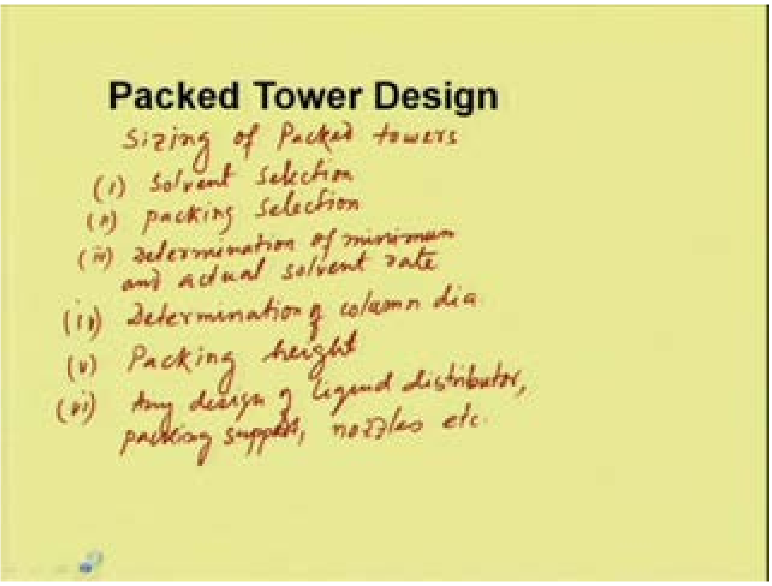

Packed Tower Design

Sizing of Packed towers
(i) Solvent selection
(ii) packing selection
(iii) determination of minimum and actual solvent rate
(iv) Determination of column dia
(v) Packing height
(vi) Any design of liquid distributor, packing support, nozzles etc.

Now for sizing of the packed towers we need to consider different steps, one is the solvent selection and second one is packing selection then we have to determine the minimum determination of minimum and actual solvent rate then determination of column diameter then the height of the column or packing height, any design of liquid distributor, packing support, nozzles etc. So this procedure has to be followed. In our pervious few lectures we have considered these steps how to what are criteria to select the solvent, how to select the different types of the packing and how to determine the minimum and actual solvent of the rate, we have seen how to determine the column diameter.

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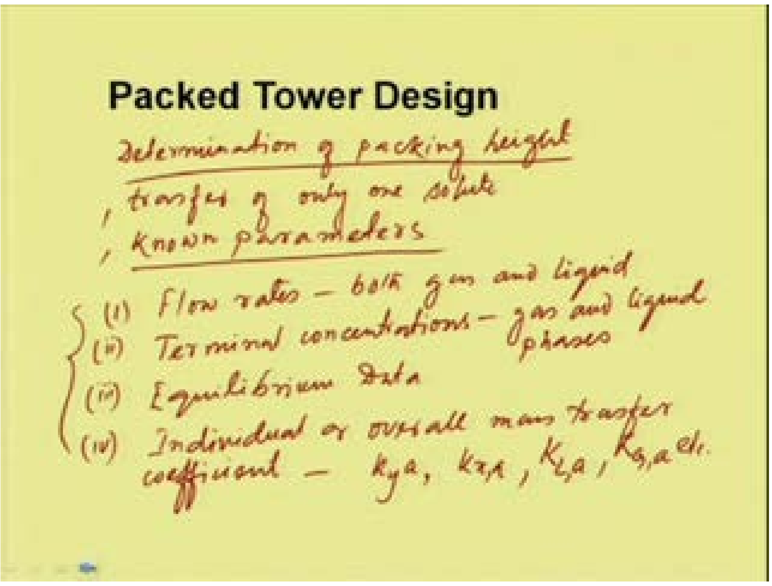

Packed Tower Design

Determination of packing height

- transfer of only one solute
- known parameters

(i) Flow rates – both gas and liquid
(ii) Terminal concentrations – gas and liquid phases
(iii) Equilibrium Data
(iv) Individual or overall mass transfer coefficient – $k_y a$, $k_x a$, $K_L a$, $K_G a$ etc.

In this lecture we will only consider determination of packing height and we will consider only transfer of one solute molecules transfer of only one solute and for the design purpose the following parameters should be known before. And the known parameters one is the flow rates flow rates both gas and liquid, terminal concentrations both gas and in liquid phases, then the equilibrium data and the individual or overall mass transfer coefficient like k y a, k x a, or capital K L a, K G a etcetera. These are the known parameters is required for the design or determination of packing height for a particular application.

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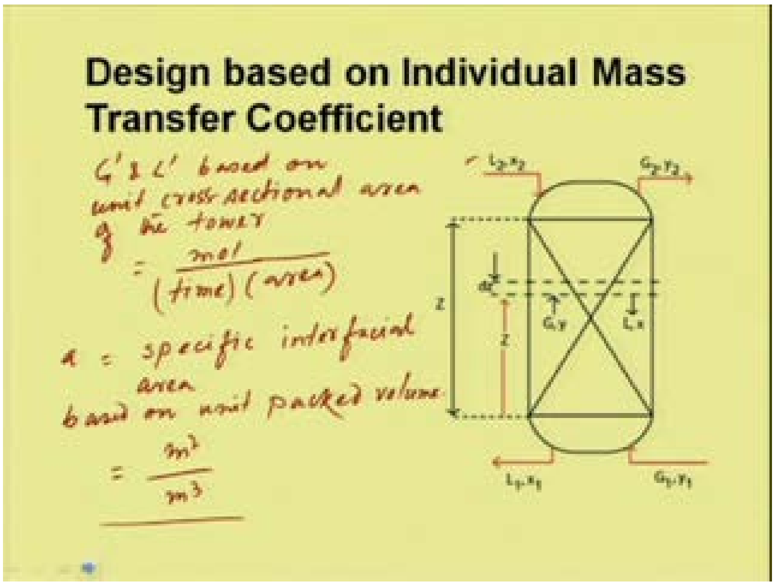

Design based on Individual Mass Transfer Coefficient

G' & L' based on unit cross sectional area of the tower

$= \frac{mol}{(time)(area)}$

a = specific interfacial area based on unit packed volume

$= \frac{m^2}{m^3}$

Now we will consider design method which is based on the individual mass transfer coefficients. For this let us consider the packed towers, so this is the height of the packing in a packed towers, Z is the total height and inlet gas rate is G 1 Y 1 and outlet gas rate is G 2 Y 2; and inlet liquid rate is L 2 X 2 and in outlet liquid rate is L 1 X 1. So, this is counter current operations in packed column; and G dash and L dash this is based on unit cross sectional area of the tower, so it has unit of mol per time into area and a is the specific interfacial area, this is basically based on unit packed volume, so the unit of a will be meter square per meter cube.

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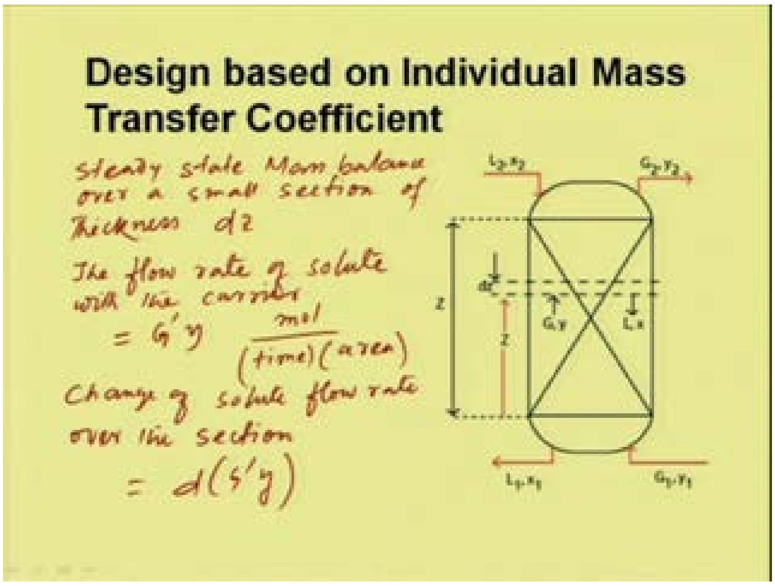

Design based on Individual Mass Transfer Coefficient

Steady state Mass balance over a small section of thickness dz

The flow rate of solute with the carrier

$= G'y \quad \frac{mol}{(time)(area)}$

Change of solute flow rate over the section

$= d(G'y)$

Now if we consider steady state operations of the column and if we consider the thickness at any point inside the tower is d z and a steady state mass balance over a small section of thickness d z will get the flow rate of solute with the carrier is equal to G dash y mol per time into area. Now the change of solute flow rate over the section change of solute flow rate over the section would be d into G dash y.

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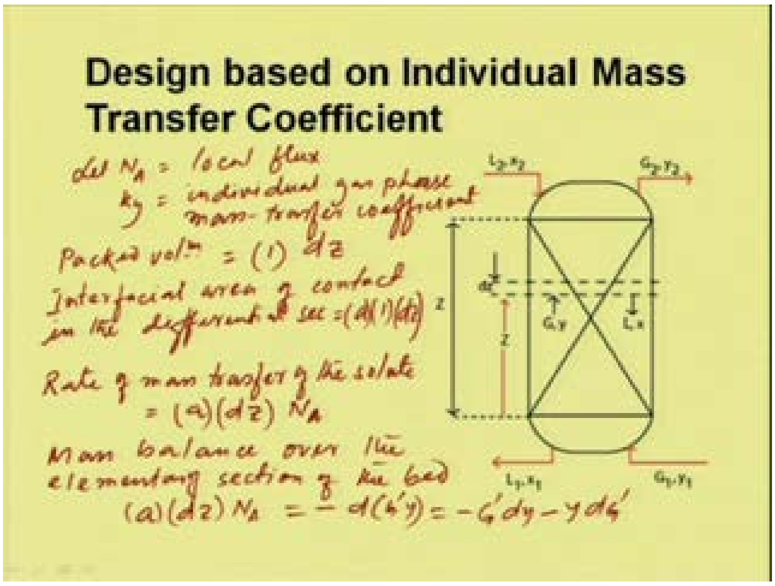

Design based on Individual Mass Transfer Coefficient

Let N_A = local flux

k_y = individual gas phase mass-transfer coefficient

Packed vol^m = (1) dz

Interfacial area of contact in the differential sec = (a)(1)(dz)

Rate of mass transfer of the solute = (a)(dz) N_A

Mass balance over the elementary section of the bed

$(a)(dz)N_A = -d(G'y) = -G'dy - y\,dG'$

Now if you consider N A is the local flux and k y is the individual gas phase mass transfer coefficient coefficient. Then the packed volume volume will be 1 into d z and the interfacial area of contact in the differential section interfacial area of contact in the differential section should be equal to a into 1 into d z. Then the rate of mass transfer of the solute should be equal to a d z into N A. Now, if you do the mass balance over the elementary section mass balance we will get a d z N A should be equal to minus d of G dash y which is equal to minus G dash d y minus y d G dash.

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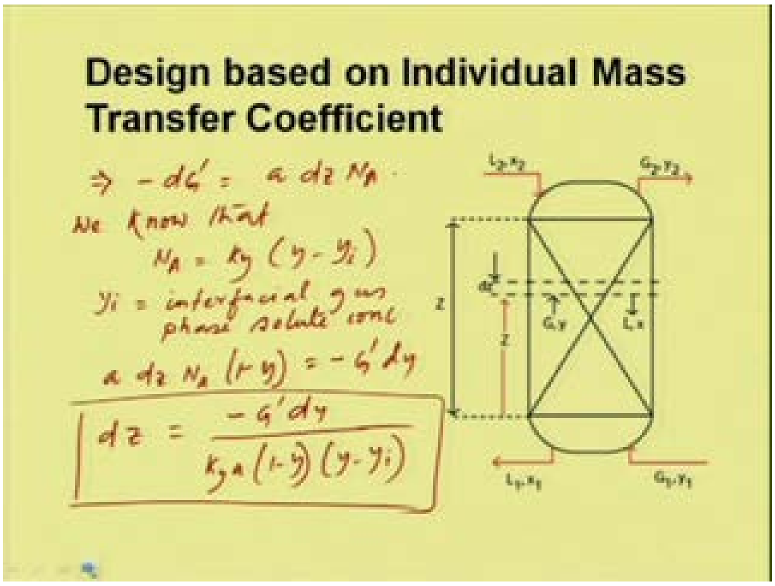

Design based on Individual Mass Transfer Coefficient

$\Rightarrow -dG' = a\,dz\,N_A$

We know that

$N_A = k_y(y - y_i)$

y_i = interfacial gas phase solute conc

$a\,dz\,N_A(1-y) = -G'dy$

$$\boxed{dz = \frac{-G'dy}{k_y a(1-y)(y-y_i)}}$$

So from this we can write minus d G dash will be a d z into N A. Now we know that N A is equal to k y into y minus y i y where y i is the interfacial concentration, interfacial gas plate solute concentration. So if we put this in this equation the equation and then rearrange then it will be a d z N A into 1 minus y is equal to minus G dash d y, so d z equal to minus G dash d y divided by k y a into 1 minus y into y minus y i, so this is the equations for d z.

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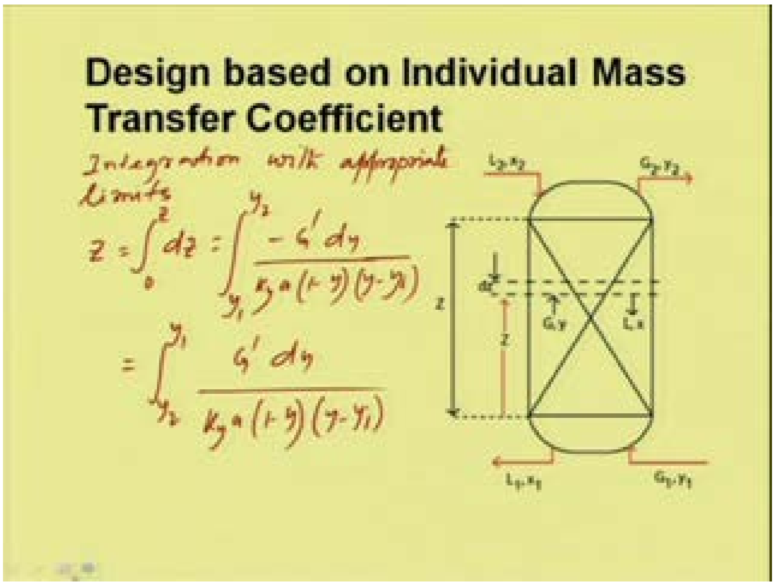

Design based on Individual Mass Transfer Coefficient

Integration with appropriate limits

$$Z = \int_0^Z dz = \int_{y_1}^{y_2} \frac{-G'dy}{k_y a(1-y)(y-y_i)}$$

$$= \int_{y_2}^{y_1} \frac{G'dy}{k_y a(1-y)(y-y_i)}$$

And then if we integrate this equation with the appropriate limits it gives z is equal to integral 0 to 2 d z will be equal to integral y 1 to y 2 minus G dash d y divided by k y a into 1 minus y into y minus y i is equal to integral y 2 to y 1 G dash d y divided by k y a into 1 minus y into y minus y i. Now, this evaluation of this integral will give you the value of z and this can be done by graphical or numerical methods.

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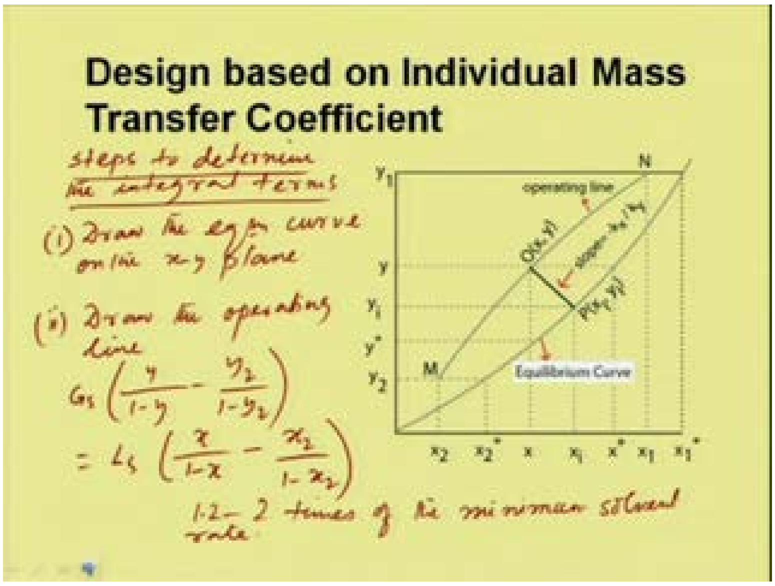

Design based on Individual Mass Transfer Coefficient

steps to determine the integral terms

(i) Draw the eqm curve on the x-y plane

(ii) Draw the operating line

$$G_s\left(\frac{y}{1-y}-\frac{y_2}{1-y_2}\right) = L_s\left(\frac{x}{1-x}-\frac{x_2}{1-x_2}\right)$$

1.2 – 2 times of the minimum solvent rate

So the procedure we can follow to determine the integral term following steps may be followed, steps to determine to the integral, the graphical methods we can follow. The steps: first will draw the equilibrium curve on the x y plane so this is the equilibrium curve which is plotted based on some values available; and then draw the operating line and then this operating line equations we know from the mass balance we can write G s y by 1 minus y minus y 2 by 1 minus y 2 is equal to L s into x by 1 minus x minus x 2 by one minus x 2. So, this is the equations of operating line. With this we can plot the operating line and if this is not given, the liquid flow rate is not given, then we can calculate how to obtain the minimum liquid flow rate and we can take a value of what 1.2 to 2 times of the minimum liquid rate and we can draw the operating line.

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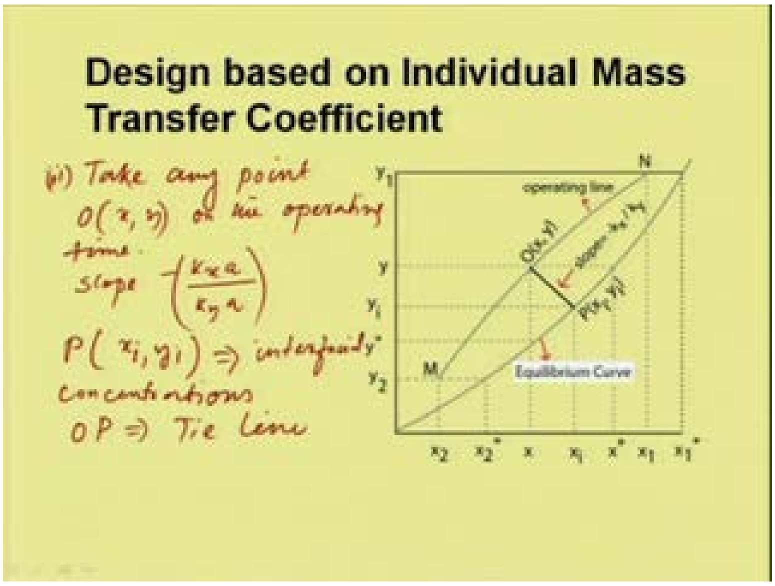

Design based on Individual Mass Transfer Coefficient

(vi) Take any point O(x, y) on the operating line.

slope $-\left(\frac{k_x a}{k_y a}\right)$

$P(x_i, y_i) \Rightarrow$ interfacial concentrations

$OP \Rightarrow$ Tie line

Now we will take any point on the operating line say at point O which is (x, y) take any point o x y on the operating line, now we know the slope of the value minus k x a by k y a, with this slope we can draw a line which is this line and which intersect at some point P which is (x i, y i) this give the interfacial concentrations corresponding to that (x, y) value, this line o p is called the tie line.

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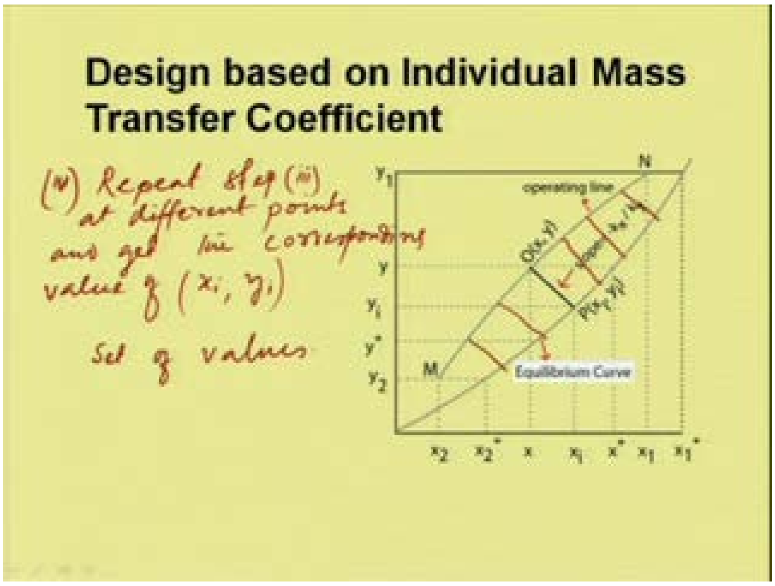

Design based on Individual Mass Transfer Coefficient

(iv) Repeat step (iii) at different points and get the corresponding value of (x_i, y_i)

Set of values

Now we can repeat this step and we can plot parallel to this line so many points on this curve, so repeat step three at different points and get the corresponding values of (x i ,y i) so then we have a set of set of values.

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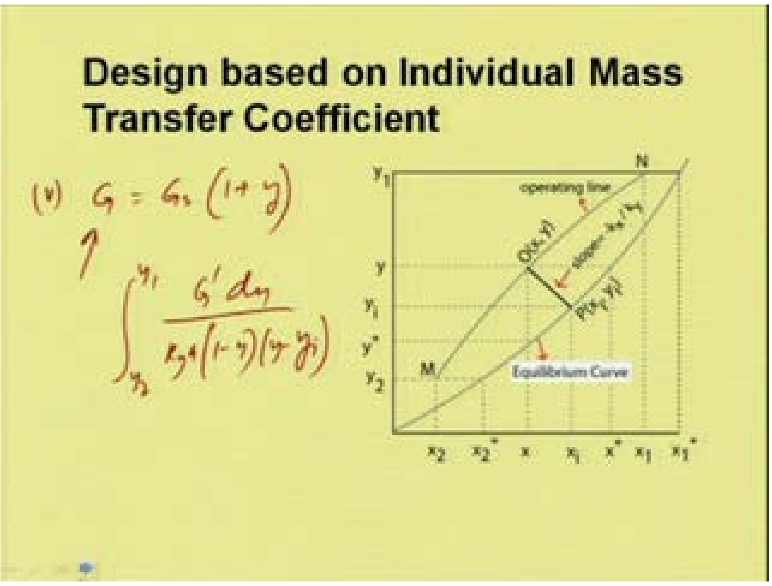

Design based on Individual Mass Transfer Coefficient

(v) $G = G_s(1+y)$

$$\int_{y_2}^{y_1} \frac{G'\,dy}{k_y a(1-y)(y-y_i)}$$

And then we can calculate at each point G is equal to G s into 1 plus y; and this we can check how at every point G is changing. We will come later how to calculate the area under the integral that is from y 2 to y 1 G dash d y by k y a 1 minus y y minus y i, so we will come with an example to calculate this.

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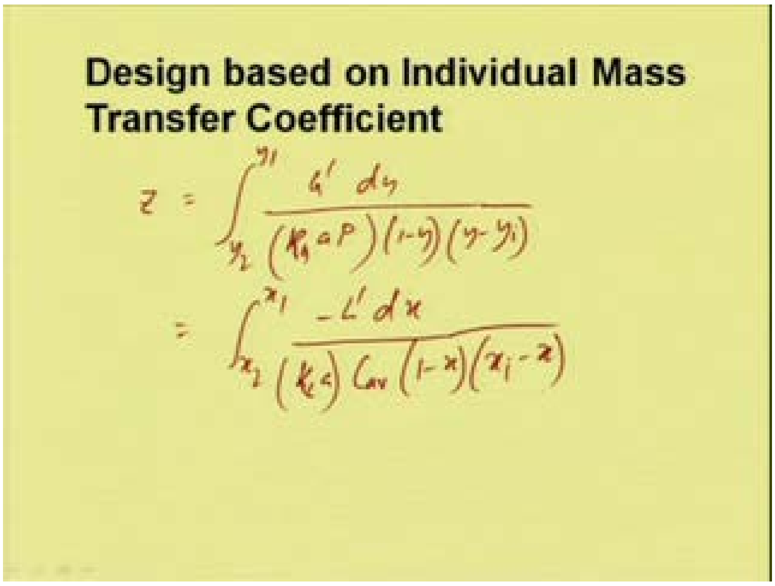

Design based on Individual Mass Transfer Coefficient

$$Z = \int_{y_2}^{y_1} \frac{G'\,dy}{(k_G a P)(1-y)(y-y_i)}$$

$$= \int_{x_2}^{x_1} \frac{-L'\,dx}{(k_x a)\,C_{av}(1-x)(x_i-x)}$$

You can use other type of individual mass transfer coefficient to calculate the values of z, which is equal to we can write integral y 2 to y 1 G dash d y divided by K G a p capital K G into 1 minus y into y minus y i or we can also use integral x 2 to x 1 minus L dash d x divided by K L a capital K L a into C a average into 1 minus x into x i minus x.

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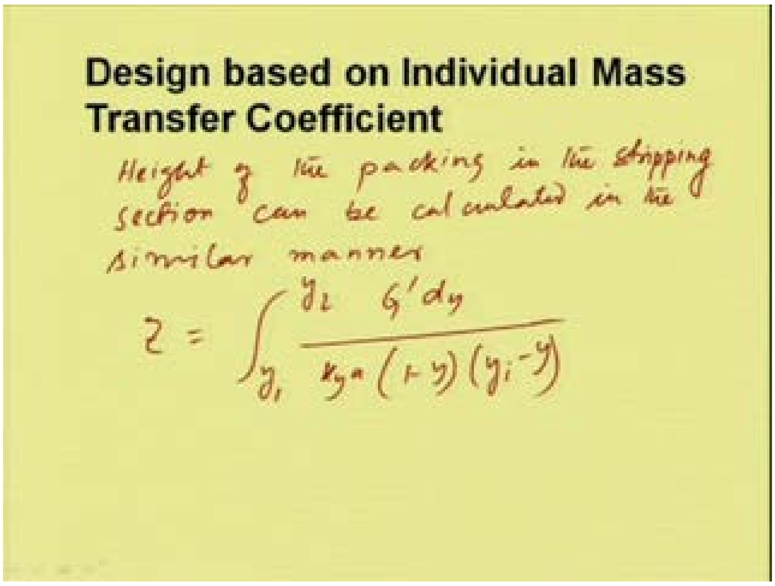

Design based on Individual Mass Transfer Coefficient

Height of the packing in the stripping section can be calculated in the similar manner

$$z = \int_{y_1}^{y_2} \frac{G' dy}{k_y a (1-y)(y_i - y)}$$

The height of the stripping section in the similar way, height of the packing in the stripping section can be calculated in the similar manner. So, the design equations we can write will be integral y 1 to y 2 G dash d y divided by k y a into 1 minus y into y i minus y.

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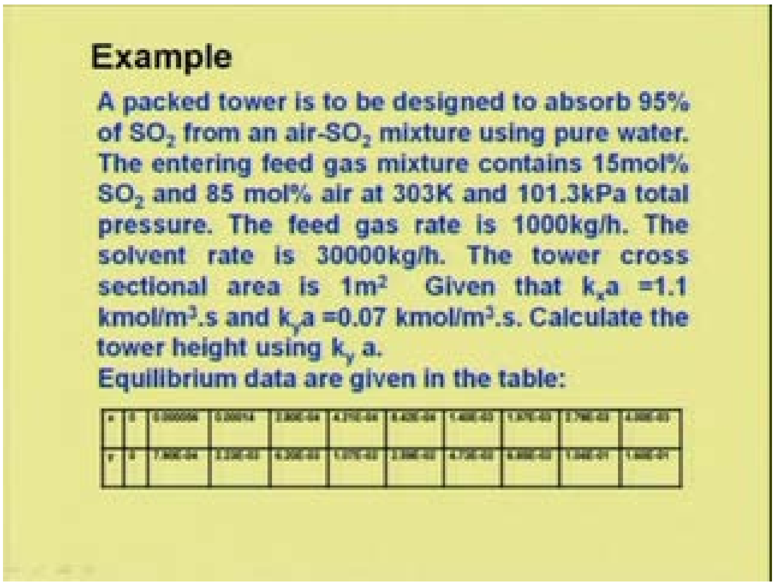

Example

A packed tower is to be designed to absorb 95% of SO_2 from an air-SO_2 mixture using pure water. The entering feed gas mixture contains 15mol% SO_2 and 85 mol% air at 303K and 101.3kPa total pressure. The feed gas rate is 1000kg/h. The solvent rate is 30000kg/h. The tower cross sectional area is 1m² Given that $k_x a$ =1.1 kmol/m³.s and $k_y a$ =0.07 kmol/m³.s. Calculate the tower height using k_y a.

Equilibrium data are given in the table:

x	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
y	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Now let us consider an example of packed tower is to be designed to absorb 95 percent of sulphur di oxide from an air. So two mixture using pure water and the entering feed gas mixture gas contains 15 mole percent sulphur di oxide and 85 percent mol at 303 kelvin and 101.3 kilo pascal total pressure. The feed gas rate is given 1000 k g per hour. The solvent rate is given thirty 30000 k g per hour. The tower cross sectional area is 1 meter square and also it is given that k x a is 1.1 k mol meter per second and k y a is 0.07 k mol per meter square per second. We have to calculate the tower height using k y a. The equilibrium data is given in this table, x and y values are given.

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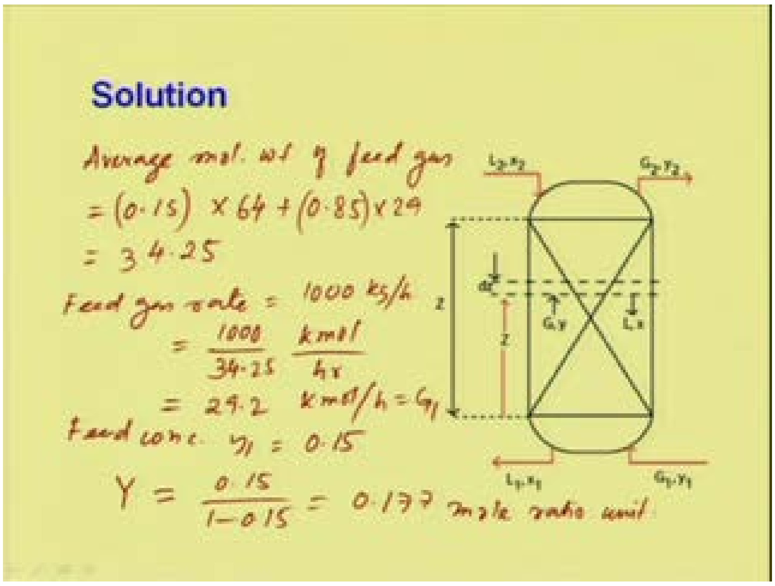

Solution

Average mol. wt of feed gas

$= (0.15) \times 64 + (0.85) \times 29$

$= 34.25$

Feed gas rate $=$ 1000 kg/h

$= \frac{1000}{34.25} \frac{kmol}{hr}$

$= 29.2$ kmol/h $= G_1$

Feed conc. $y_1 = 0.15$

$Y = \frac{0.15}{1-0.15} = 0.177$ mole ratio unit

Now we will calculate the average molecular weight of feed gas, so the feed gas is entering as 15 mol percent of SO2 so 0.15 into 64 plus 0.85 mol percent of air into 29 so this will be 34.25. Now the feed gas rate is given, feed gas rate is equal to 1000 k g per hour, so we will convert it to kilo mol per hour which will be 1000 divided by 34.25 k mol per hour which is equal 29.2 k mol per hour and this we can define as G 1. Now, feed concentration as we said, feed concentration y 1 is 0.15 mol fraction, so capital Y we can calculate 0.15 by 1 minus 0.15 which is equal to 0.177 mol ratio unit.

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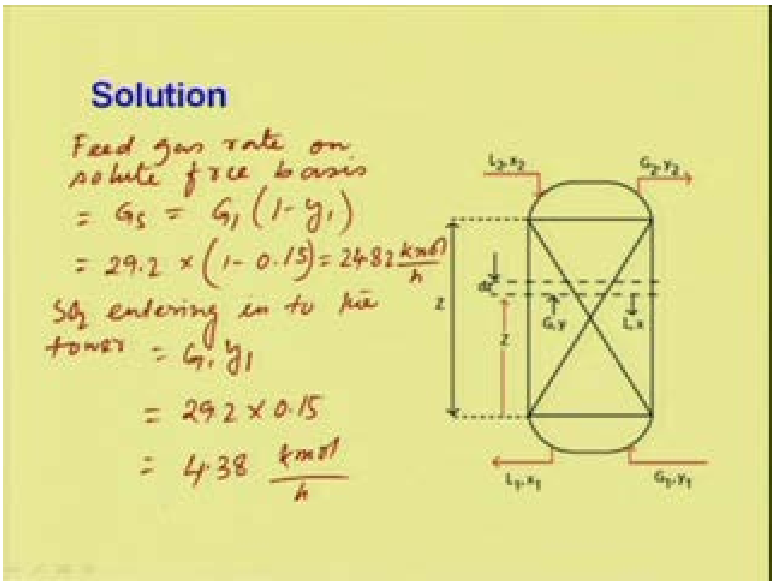

Solution

Feed gas rate on solute free basis

$= G_S = G_1(1-y_1)$

$= 29.2 \times (1-0.15) = 24.82\ \frac{kmol}{h}$

SO_2 entering in to the tower $= G_1 y_1$

$= 29.2 \times 0.15$

$= 4.38\ \frac{kmol}{h}$

Now the feed gas rate on solute free basis we can calculate, solute free basis is equal to G s which is equal to G 1 into 1 minus y 1 which we can write 29.2 into 1 minus 0.15, so this will be 24.82 k mol per hour. Now SO 2 entering into the tower is equal to G 1 y 1 which is equal to 29.2 into 0.15 this is equals 4.38 k mol per hour. This is the entering sulphur di oxide concentration into the tower.

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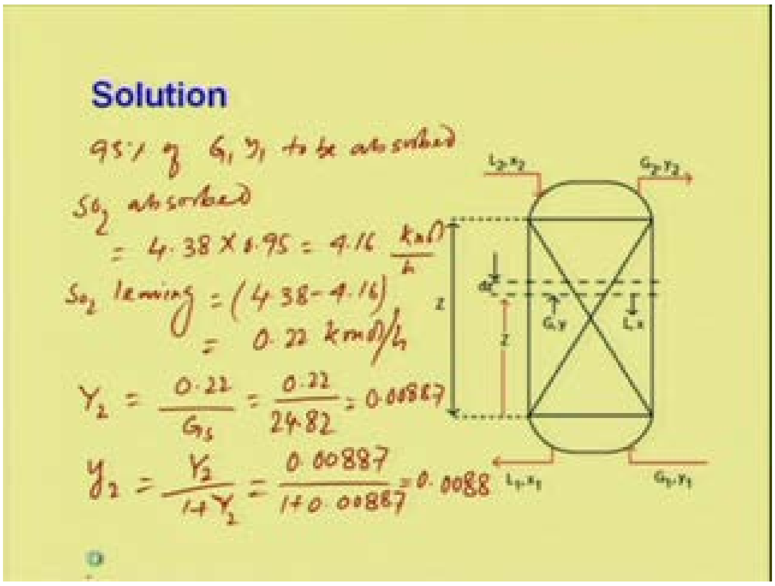

Solution

95% of $G_1\ y_1$ to be absorbed

SO_2 absorbed

$$= 4.38 \times 0.95 = 4.16\ \frac{kmol}{h}$$

$$SO_2 \text{ leaving} = (4.38 - 4.16) = 0.22\ kmol/h$$

$$Y_2 = \frac{0.22}{G_s} = \frac{0.22}{24.82} = 0.00887$$

$$y_2 = \frac{Y_2}{1+Y_2} = \frac{0.00887}{1+0.00887} = 0.0088$$

95 percent of G 1 y 1 to be observed, so then SO 2 absorbed should be 4.38 into 0.95 is equal to 4.16 k mol per hour. Now SO 2 leaving is equal to 4.38 minus 4.16 which is equal to 0.22 k mol per hour. Now, we can calculate concentration capital Y 2 is equal to 0.22 by G s which is 0.22 by 24.82 which is equal to 0.00887 and Y 2 we can calculate capital Y 2 by 1 plus Y 2 which is equal to 0.00887 divided by 1 plus 0.00887 which is equals to 0.0088.

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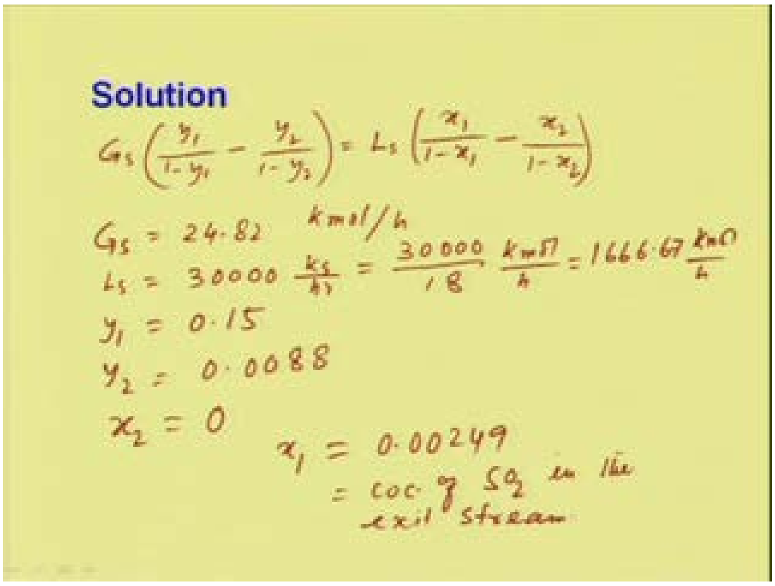

Solution

$$G_s\left(\frac{y_1}{1-y_1} - \frac{y_2}{1-y_2}\right) = L_s\left(\frac{x_1}{1-x_1} - \frac{x_2}{1-x_2}\right)$$

$G_s = 24.82$ kmol/h

$$L_s = 30000\ \frac{kg}{h} = \frac{30000}{18}\ \frac{kmol}{h} = 1666.67\ \frac{kmol}{h}$$

$y_1 = 0.15$

$y_2 = 0.0088$

$x_2 = 0$

$x_1 = 0.00249$

= conc of SO_2 in the exit stream

Now we will calculate the exit concentration of sulphur dioxide in the liquid phase, to do that we know the overall balance equation which is G s into y 1 by 1 minus y 1 minus y 2 by 1 minus y 2 is equal to L s into x 1 by 1 minus x 1 minus x 2 divided by 1 minus x 2, we know G s which is equal to 24.82 k mol per hour and L s is equal to 30000 k g per hour which is equal to 30000 divided by 18 k mol per hour which is equal to 1666.67 k mol per hour; y 1 is given which is 0.15, y 2; we have calculated 0.0088 and pure water is used to absorb SO 2 it is 0, if we substitute these values then x 1 is equal to 0.00249. So this is the concentration of SO 2 in the exit stream.

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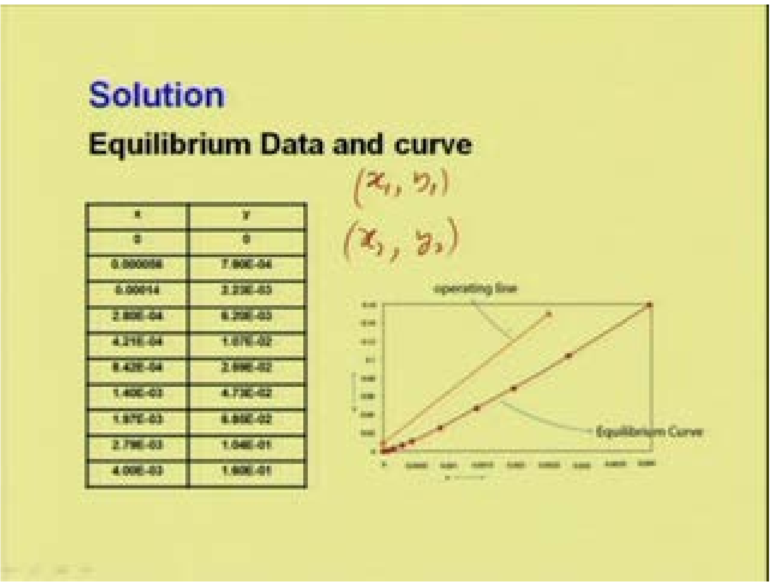

Solution

Equilibrium Data and curve

x	y
0	0
0.000056	7.90E-04
0.00014	2.23E-03
2.80E-04	6.20E-03
4.21E-04	1.07E-02
8.42E-04	2.89E-02
1.40E-03	4.73E-02
1.97E-03	6.85E-02
2.79E-03	1.04E-01
4.00E-03	1.60E-01

Now the equilibrium data which is given is plotted over here, we know the (x 1, y 1) and (x 2, y 2). With the equilibrium data given we can plot this is the equilibrium curve and with the data of (x 1 y 1) and (x 2 y 2) we can plot the operating line curve.

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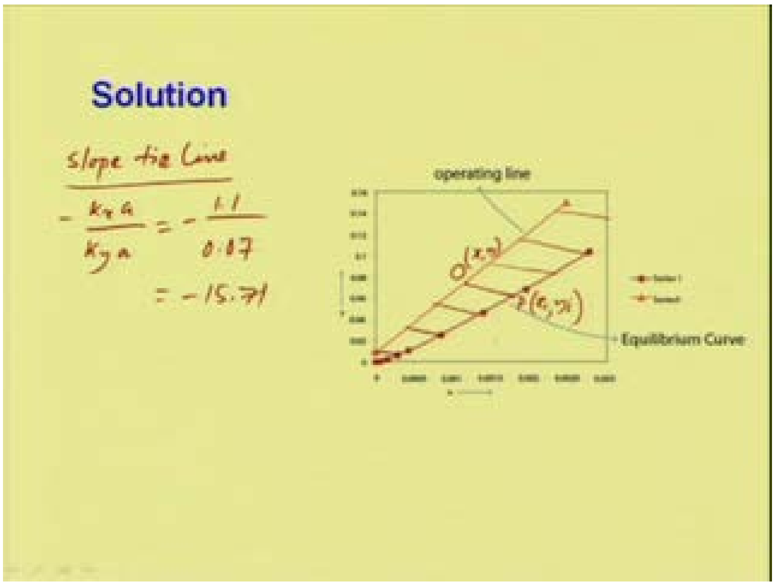

Solution

slope tie Curve

$$-\frac{k_x a}{k_y a} = -\frac{1.1}{0.07}$$

$$= -15.71$$

Now the procedure to be followed we will locate a point anywhere on the curve and the slope of the tie line can be calculated, minus k x a divided by k y a, and which is equal to minus 1.1 by 0.07 which is equal to minus 15.71. This is the equation of tie line, with this we can plot the line with that flow and we will get at point o and this is p and we know the (x i, y i), and this is point (x, y). Similarly, we can draw different parallel line to this and a different point we can calculate sets of x and y values and x i and y i values.

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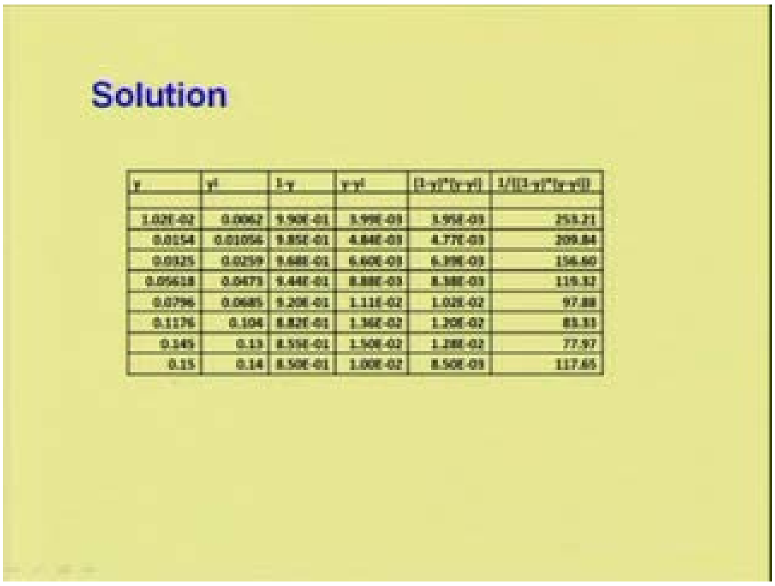

Solution

y	yi	1-y	y-yi	(1-y)*(y-yi)	1/[(1-y)*(y-yi)]
1.02E-02	0.0062	9.90E-01	3.99E-03	3.95E-03	253.21
0.0154	0.01056	9.85E-01	4.84E-03	4.77E-03	209.84
0.0325	0.0259	9.68E-01	6.60E-03	6.39E-03	156.60
0.05618	0.0473	9.44E-01	8.88E-03	8.38E-03	119.32
0.0796	0.0685	9.20E-01	1.11E-02	1.02E-02	97.88
0.1176	0.104	8.82E-01	1.36E-02	1.20E-02	83.33
0.145	0.13	8.55E-01	1.50E-02	1.28E-02	77.97
0.15	0.14	8.50E-01	1.00E-02	8.50E-03	117.65

The following table shows the values from initial to the final, this is y 2 y 1 and this is y 2, so this in this point we have got the different values of y i and from that we can calculate y 1 by y minus 1 into y minus y i.

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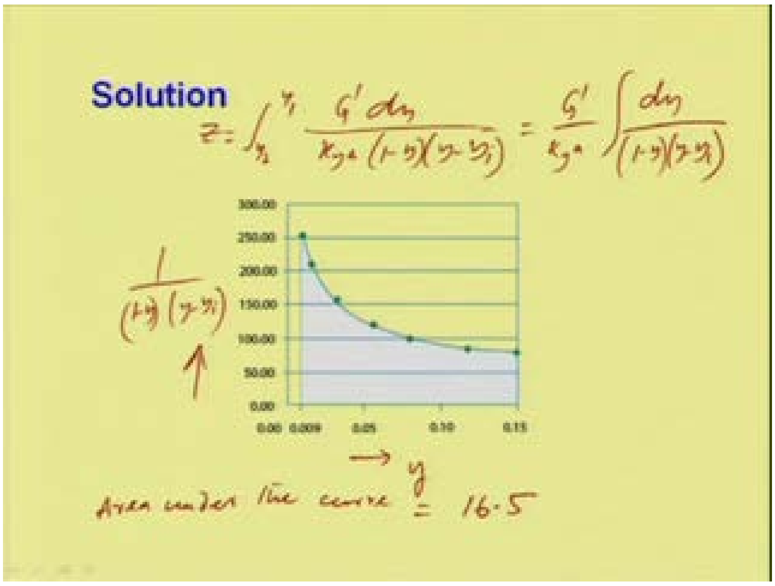

Solution

$$z = \int_{y_2}^{y_1} \frac{G' \, dy}{K_y a (1-y)(y-y_i)} = \frac{G'}{K_y a} \int \frac{dy}{(1-y)(y-y_i)}$$

Area under the curve = 16.5

Now with that we know the equation which is z is equal to integral y 2 to y 1 G dash d y divided by K y a 1 minus y into y minus y i which is equal to we can write G dash by K y a integral d y by 1 minus y into y minus y i, so this area under the curve if we plot 1 by 1 minus y into y minus y i versus y then the area under this curve is equal to 16.5.

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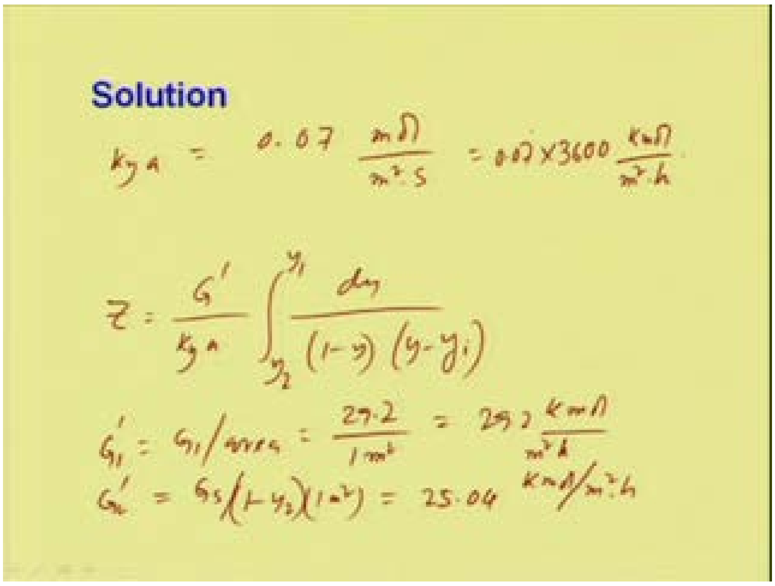

Solution

$$K_y a = 0.07 \frac{\text{kmol}}{m^2 \cdot s} = 0.07 \times 3600 \frac{\text{kmol}}{m^2 \cdot h}$$

$$z = \frac{G'}{K_y a} \int_{y_2}^{y_1} \frac{dy}{(1-y)(y-y_i)}$$

$$G'_1 = G_1/\text{area} = \frac{29.2}{1 m^2} = 29.2 \frac{\text{kmol}}{m^2 h}$$

$$G'_2 = G_s (1-y_2)(1 m^2) = 25.04 \text{ kmol}/m^2 \cdot h$$

Now we know k y a, which is 0.07 mol per meter square second which is equal to 0.07 into 3600 k mol per meter square hour. Now the z which is equal to G dash by k y a into integral y 2 to y 1 d y by 1 minus y into y minus y i. So we have to calculate G 1 dash first which is G 1 by area, area is given 1 meter square, so 29.2 by 1 meter square which is 29.2 k mol per meter square hour. Now G 2 dash is equal to G s divided by 1 minus y 2 into 1 meter square which is equal to 25.04 k mol per meter square hour.

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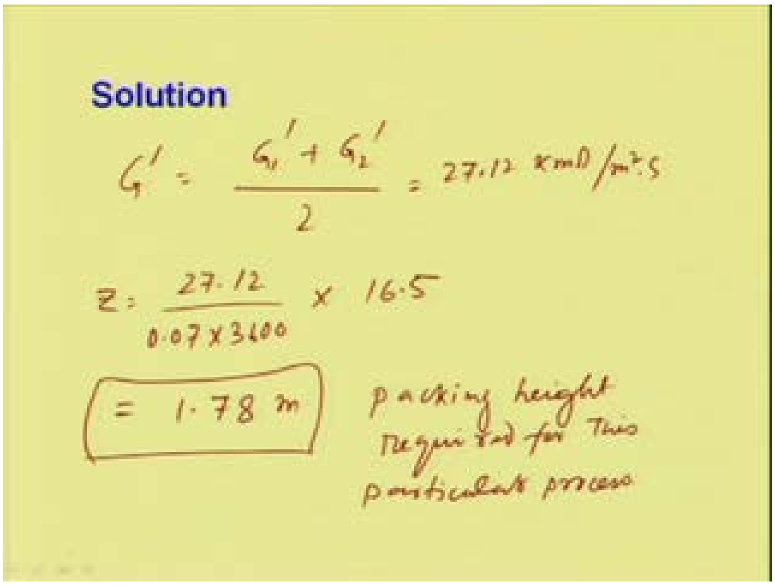

Solution

$$G' = \frac{G_1' + G_2'}{2} = 27.12 \text{ kmol}/\text{m}^2\text{s}$$

$$z = \frac{27.12}{0.07 \times 3600} \times 16.5$$

$$\boxed{= 1.78\ m}$$

packing height required for this particular process

Now, we can get G dash which is G 1 dash plus G 2 dash divided by 2, which is equal to 27.12 k mol per meter square second. Now Z is equal to 27.12 divided by 0.07 into 3600 into 16.5, so this is equal to 1.78 meter. So this is the packed height required for this particular operation, particular process.

Thank you.