CE407 SEPARATIONS

Lecture 22

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School of Engineering and Applied Sciences

Mass Transfer Correlations for Packed Towers

- In the previous lecture we saw some methods for estimating k_x and k_y
- When it comes to packed towers there are some issues
  - The geometry of the packing is not like the simpler cases where we have existing correlations
  - a is dependent on the flow rates, packing design, surface tension, viscosity, etc.
- Fortunately, there are correlations for H_x and H_y directly

$$\boxed{H_x = (0.9\,ft)\left[\frac{G_x/\mu}{\left(1500\ {}^{lb}/_{ft^2\,hr}\right)/(0.891\,cP)}\right]^{0.3}\left(\frac{S_c}{381}\right)^{0.5}\frac{1}{f_p}}$$

- This was arrived at by taking experimental data for O_2 in water
  - This system is dominated by liquid film resistance, so the experimental measurements are essentially that of transport through the liquid film versus the combination
  - G_x is mass velocity and must be the same units as appear in the correlation, ${}^{lb}/_{ft^2\,hr}$
- Data correlated to show that $H_x \propto \left(\frac{G_x}{\mu}\right)^{0.3}(S_c)^{0.5}$
- A value of 0.9 feet corresponds to $G_x = 1500\ {}^{lb}/_{ft^2\,hr}$, $\mu = 0.891\,cP$, $S_c = 381$, and $f_p = 1$

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Mass Transfer Correlations for Packed Towers

- The correlation on the previous page was developed using water as the liquid – use caution when applying it to other liquids
- $\boldsymbol{f_p}$ accounts for the type of packing used
  - Be sure to use $\boldsymbol{f_p}$ and not $\boldsymbol{F_p}$
  - $\boldsymbol{F_p}$ is used in calculations of pressure drop

TABLE 18.1
Characteristics of dumped tower packings[12,15b,27]

Type	Material	Nominal size, in.	Bulk density,† lb/ft³	Total area,† ft²/ft³	Porosity ε	Packing factors‡ F_p	Packing factors‡ f_p
Raschig rings	Ceramic	$\frac{1}{2}$	55	112	0.64	580	1.52§
		1	42	58	0.74	155	1.36§
		$1\frac{1}{2}$	43	37	0.73	95	1.0
		2	41	28	0.74	65	0.92§
Pall rings	Metal	1	30	63	0.94	56	1.54
		$1\frac{1}{2}$	24	39	0.95	40	1.36
		2	22	31	0.96	27	1.09
	Plastic	1	5.5	63	0.90	55	1.36
		$1\frac{1}{2}$	4.8	39	0.91	40	1.18
Berl saddles	Ceramic	$\frac{1}{2}$	54	142	0.62	240	1.58§
		1	45	76	0.68	110	1.36§
		$1\frac{1}{2}$	40	46	0.71	65	1.07§
Intalox saddles	Ceramic	$\frac{1}{2}$	46	190	0.71	200	2.27
		1	42	78	0.73	92	1.54
		$1\frac{1}{2}$	39	59	0.76	52	1.18
		2	38	36	0.76	40	1.0
		3	36	28	0.79	22	0.64
Super Intalox saddles	Ceramic	1	—	—	—	60	1.54
		2	—	—	—	30	1.0
IMTP	Metal	1	—	—	0.97	41	1.74
		$1\frac{1}{2}$	—	—	0.98	24	1.37
		2	—	—	0.98	18	1.19
Hy-Pak	Metal	1	19	54	0.96	45	1.54
		$1\frac{1}{2}$	—	—	—	29	1.36
		2	14	29	0.97	26	1.09
Tri-Pac	Plastic	1	6.2	85	0.90	28	—
		2	4.2	48	0.93	16	—

†Bulk density and total area are given per unit volume of column.

‡Factor F_p is a pressure drop factor and f_p a relative mass-transfer coefficient. Factor f_p is discussed on page 603 in the paragraph "Performance of Other Packings." Its use is illustrated in Example 18.7.

§Based on NH_3–H_2O data; other factors based on CO_2–NaOH data.

Mass Transfer Correlations for Packed Towers

$$H_y = (1.4\, ft)\left[\frac{G_y}{500\ {}^{lb}/_{ft^2\, hr}}\right]^{0.3}\left[\frac{1500\ {}^{lb}/_{ft^2\, hr}}{G_x}\right]^{0.4}\left(\frac{S_c}{0.66}\right)^{0.5}\frac{1}{f_p}$$

- Correlation similarly derived for an air-ammonia-water system
  - High solubility of ammonia in water leads to system being dominated by gas film resistance
- G_x and G_y are mass velocities and must be in the same units as appear in the correlation, ${}^{lb}/_{ft^2\, hr}$
- Notice that G_y appears in the H_y correlation but not in the H_x correlation
  - This is because gas flow rates are specified to avoid flooding in the tower and therefore are usually in a set range for a given liquid flow

Mass Transfer Correlations for Packed Towers

- Use arithmetic averages of mass velocities at the top and bottom of the tower

$$G_x = \frac{(G_x)_a + (G_x)_b}{2}$$

$$G_y = \frac{\left(G_y\right)_a + \left(G_y\right)_b}{2}$$

Overall Mass Transfer Coefficients

Overall Heights of Transfer Units:

$$H_{Oy} = H_y + \frac{m}{L/V} H_x$$

$$H_{Ox} = H_x + \frac{L/V}{m} H_y$$

- $y_i = m x_i$
- **L and V are molar flow rates**

Packed Tower HTU Example – problem statement

- 720 mol/hr stream of toluene contaminated oil (95 mole percent oil, 5 mole percent toluene) is to be cleaned by countercurrent contact with air in a stripping tower operating at 25 C and atmospheric temperature.
- Tower is packed with 1” plastic Pall rings
- Exiting liquid must have a toluene mole fraction equal to no more than 0.001
- Entering air is pure and is at 1.078 times the minimum.
- The tower diameter is 17”
- Under the proposed operating conditions $H_x = 1.0\ ft$
- Toluene will follow Raoult’s Law and has a vapor pressure of 0.0380 atm
- The oil has MW = 170, $\rho = 0.730\ \frac{gm}{cm^3}$, $\mu = 0.86\ cP$
- Due to low toluene mole fractions the physical properties may be approximated as those of pure oil

- Using $\boldsymbol{H_{Oy}}$ and $\boldsymbol{N_{Oy}}$, determine the required Packed Height
    - Use the “Usual Assumptions”

$$H_y = (1.4\ ft)\left[\frac{G_y}{500\ {}^{lb}/_{ft^2\ hr}}\right]^{0.3}\left[\frac{1500\ {}^{lb}/_{ft^2\ hr}}{G_x}\right]^{0.4}\left(\frac{S_c}{0.66}\right)^{0.5}\frac{1}{f_p}$$

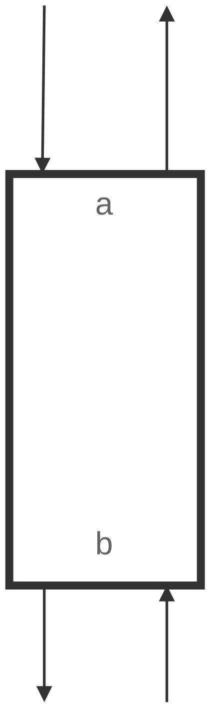
$$H_{Oy} = H_y + \frac{m}{L/V}H_x$$

$$N_{Oy} = \frac{y_b - y_a}{\overline{(y-y^*)}_{lm}} \qquad \overline{(y-y^*)}_{lm} = \frac{(y-y^*)_a - (y-y^*)_b}{\ln\left[\frac{(y-y^*)_a}{(y-y^*)_b}\right]}$$

$$Z_t = H_{Oy} * N_{Oy}$$

Packed Tower HTU Example – Preliminary calculations

- 1 hour basis



Packed Tower HTU Example – minimum and actual air flow

- Due to the dilute nature and the fact that this is a stripping operation, minimum air can be calculated with the assumption that

- Actual Air Flow

Packed Tower HTU Example -Mass rates and Mass Fluxes

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APPENDIX 18

Diffusivities and Schmidt Numbers of Gases in Air (25 °C and 1 atm)

Gas	Volumetric diffusivity D_v, ft²/h	$N_{Sc} = \frac{\mu}{\rho D_v}$ ‡
Acetic acid	0.413	1.24
Acetone	0.32§	1.60
Ammonia	0.836	0.61
Benzene	0.299	1.71
n-Butyl alcohol	0.273	1.88
Carbon dioxide	0.535	0.96
Carbon tetrachloride	0.26§	1.97
Chlorine	0.43§	1.19
Chlorobenzene	0.24§	2.13
Ethane	0.49§	1.04
Ethyl acetate	0.278	1.84
Ethyl alcohol	0.396	1.30
Ethyl ether	0.302	1.70
Hydrogen	2.37	0.22
Methane	0.74§	0.69
Methyl alcohol	0.515	1.00
Naphthalene	0.199	2.57
Nitrogen	0.70§	0.73
n-Octane	0.198	2.62
Oxygen	0.690	0.74
Phosgene	0.31§	1.65
Propane	0.36§	1.42
Sulfur dioxide	0.44§	1.16
Toluene	0.275	$\boxed{1.86}$
Water vapor	0.853	0.60

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‡ The value of μ/ρ is that for pure air, 0.512 ft²/h.
§ Calculated by Eq. (21.25).

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		2	—	—	—	30	1.0
IMTP	Metal	1	—	—	0.97	41	1.74
		$1\frac{1}{2}$	—	—	0.98	24	1.37
		2	—	—	0.98	18	1.19
Hy-Pak	Metal	1	19	54	0.96	45	1.54
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		2	4.2	48	0.93	16	—

†Bulk density and total area are given per unit volume of column.
‡Factor F_p is a pressure drop factor and f_p a relative mass-transfer coefficient. Factor f_p is discussed on page 603 in the paragraph "Performance of Other Packings." Its use is illustrated in Example 18.7.
§Based on NH_3–H_2O data; other factors based on CO_2–NaOH data.

Mass Transfer Coefficients

$$H_y = (1.4\,ft)\left[\frac{G_y}{500\ {}^{lb}/_{ft^2\,hr}}\right]^{0.3}\left[\frac{1500\ {}^{lb}/_{ft^2\,hr}}{G_x}\right]^{0.4}\left(\frac{S_c}{0.66}\right)^{0.5}\frac{1}{f_p}$$

$$H_y = (1.4\,ft)\left[\frac{809\,\frac{lb_m}{ft^2hr}}{500\ {}^{lb}/_{ft^2\,hr}}\right]^{0.3}\left[\frac{1500\ {}^{lb}/_{ft^2\,hr}}{165\,\frac{lb_m}{ft^2hr}}\right]^{0.4}\left(\frac{1.86}{0.66}\right)^{0.5}\frac{1}{1.36} = 4.8\,ft$$

$H_x = 1.0\,ft$ given in problem statement

Overall Mass Transfer Coefficient

Overall Height of Transfer Unit

$$H_{Oy} = H_y + \frac{m}{L/V} H_x$$ where $y_i = m x_i$

Number of Transfer Units

$$N_{Oy} = \frac{y_b - y_a}{\overline{(y - y^*)}_{lm}}$$

$$\overline{(y - y^*)}_{lm} = \frac{(y - y^*)_a - (y - y^*)_b}{\ln\left[\frac{(y - y^*)_a}{(y - y^*)_b}\right]}$$

Number of Transfer Units and Packed Height

$$\overline{(y-y^*)}_{lm} = \frac{(y-y^*)_a - (y-y^*)_b}{\ln\left[\frac{(y-y^*)_a}{(y-y^*)_b}\right]}$$

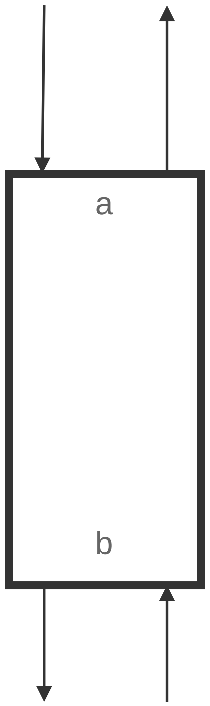
Packed Tower HTU Example – Preliminary calculations

- 1 hour basis

$L_a = 720$ mol
$x_a = 0.05$

$L_c = 0.95 * 720 = 684$ mol oil

$(L_{tol})_a = 0.05 * 720 = 36$ mol tol



$V_c = same$
$(V_{tol})_a = 36 - 0.685 = 35.315\ mol$
$y_a = ?$

$L_c =$ 684 mol oil
$x_b = 0.001$

$V_b = V_c = ?$
$y_b = 0$

- $x_b = 0.001 = \frac{(L_{tol})_b}{(L_{tol})_b + 684} \rightarrow (L_{tol})_b = 0.685\ \mathrm{mol}$

Packed Tower HTU Example – minimum and actual air flow

- Due to the dilute nature and the fact that this is a stripping operation, minimum air can be calculated with the assumption that

$$(y_a)_{min} = y^*(x_a) = \frac{P_{tol}^{sat}}{P}\, x_a$$

$$(y_a)_{min} = y^*(x_a) = \frac{0.038\, atm}{1\, atm}\, 0.05 = 0.0019$$

$$(y_a)_{min} = 0.0019 = \frac{(V_{tol})_a}{(V_{tol})_a + (V_c)_{min}} = \frac{35.315}{35.315 + (V_c)_{min}} \rightarrow (V_c)_{min} = 18551.527\ \mathrm{mol}$$

- Actual Air Flow $V_c = 1.078 * (V_c)_{min} = 19998.546\, mol \approx 20000\, mol$

$$y_a = \frac{(V_{tol})_a}{(V_{tol})_a + V_c} = \frac{35.315}{35.315 + 20{,}000} = 0.001763$$

Packed Tower HTU Example - Mass rates and Mass Fluxes

- $(SG_x)_a = \left[\left(684\ \frac{mol\ oil}{hr}\right) * \left(170\ \frac{g}{mol\ oil}\right) + \left(36\frac{mol\ tol}{hr}\right) * \left(92.14\frac{g}{mol\ tol}\right)\right] * \frac{1\ lb_m}{453.6\ g} = 263.7\ \frac{lb_m}{hr}$
- $(SG_y)_a = \left[\left(20{,}000\ \frac{mol\ air}{hr}\right) * \left(28.84\ \frac{g}{mol\ air}\right) + \left(35.315\frac{mol\ tol}{hr}\right) * \left(92.14\frac{g}{mol\ tol}\right)\right] * \frac{1\ lb_m}{453.6\ g} = 1279\ \frac{lb_m}{hr}$
- $(SG_x)_b = \left[\left(684\ \frac{mol\ oil}{hr}\right) * \left(170\ \frac{g}{mol\ oil}\right) + \left(0.685\frac{mol\ tol}{hr}\right) * \left(92.14\frac{g}{mol\ tol}\right)\right] * \frac{1\ lb_m}{453.6\ g} = 256.5\ \frac{lb_m}{hr}$
- $(SG_y)_b = \left[\left(20{,}000\ \frac{mol\ air}{hr}\right) * \left(28.84\ \frac{g}{mol\ air}\right)\right] * \frac{1\ lb_m}{453.6\ g} = 1272\ \frac{lb_m}{hr}$
- $\overline{(SG_x)} = arithmetic\ mean$ of liquid flow at a and b $= 260.1\ \frac{lb_m}{hr}$
- $\overline{(SG_y)} = arithmetic\ mean$ of vapor flow at a and b $= 1275.5\ \frac{lb_m}{hr}$
- S = Superficial Cross-sectional area $= \frac{\pi D^2}{4} = \frac{\pi\,(^{17}/_{12})^2}{4} = 1.576\ ft^2$
- $\overline{G_x} = \frac{\overline{(SG_x)}}{S} = \frac{260.1\frac{lb_m}{hr}}{1.576\ ft^2} = 165\ \frac{lb_m}{ft^2 hr}$ Liquid Mass Flux
- $\overline{G_y} = \frac{\overline{(SG_y)}}{S} = \frac{1275.5\frac{lb_m}{hr}}{1.576\ ft^2} = 809\ \frac{lb_m}{ft^2 hr}$ Vapor Mass Flux

APPENDIX 18

DIFFUSIVITIES AND SCHMIDT NUMBERS FOR GASES IN AIR AT 25 °C AND 1 ATM

Gas	Volumetric diffusivity D_v, ft²/h	$N_{Sc} = \frac{\mu}{\rho D_v}$ ‡
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$H_x = 1.0\,ft$ given in problem statement

Overall Mass Transfer Coefficient

Overall Height of Transfer Unit

$$H_{Oy} = H_y + \frac{m}{L/V} H_x$$

where $y_i = m x_i$

- $L/V = \frac{720}{20{,}035} = 0.0359$ at a
- $L/V = \frac{684}{20{,}000} = 0.0342$ at b
- $L/V = 0.0351$ average

- $m = 0.0384$ vapor pressure of toluene

$$H_{Oy} = 4.8\,ft + \frac{0.0384}{0.0351} * 1.0\,ft = 5.9\,ft$$

Number of Transfer Units

$$N_{Oy} = \frac{y_b - y_a}{\overline{(y - y^*)}_{lm}}$$

$$\overline{(y - y^*)}_{lm} = \frac{(y - y^*)_a - (y - y^*)_b}{\ln\left[\frac{(y - y^*)_a}{(y - y^*)_b}\right]}$$

- $y_a = 0.001763$
- $y_b = 0$
- $y_a^* = m * x_a = 0.038 * 0.05 = 0.0019$
- $y_b^* = m * x_b = 0.038 * 0.001 = 0.000038$
- $y_a - y_a^* = 0.001763 - 0.0019 = -0.000137$
- $y_b - y_b^* = 0 - 0.000038 = -0.000038$

Number of Transfer Units and Packed Height

$$\overline{(y-y^*)}_{lm} = \frac{(y-y^*)_a - (y-y^*)_b}{\ln\left[\frac{(y-y^*)_a}{(y-y^*)_b}\right]}$$

$$\overline{(y-y^*)}_{lm} = \frac{-0.000137 - (-0.000038)}{\ln\left[\frac{-0.000137}{-0.000038}\right]} = -7.72 * 10^{-5}$$

$$N_{Oy} = \frac{y_b - y_a}{\overline{(y-y^*)}_{lm}} = \frac{0 - 0.001763}{-7.72 * 10^{-5}} = 22.84$$

- $\boxed{Z_t = H_{Oy} * N_{Oy} = 5.9\ ft * 22.84 = 135\ ft\ \ packed\ height}$