ESTIMATION OF MASS-TRANSFER COEFFICIENTS FOR PACKED TOWERS

Correlations for experimental coefficients can be expressed in terms of H_L and H_G or $k'_x a$ and $k'_y a$, which are related by Eqs. (10.6-39) and (10.6-40). For the first generation of packings, such as Raschig rings and Berl saddles, extensive correlations are available (T1). However, comprehensive data on the individual coefficients H_L and H_G for the newer packings, which have higher mass-transfer coefficients and capacity, are not generally available. These newer packings are more commonly used today.

However, as an alternative method for comparing the performance of different types and sizes of these newer random packings, the system CO_2–air–NaOH solution is often used (P2, S4). Air containing 1.0 mole CO_2 at 24°C (75°F) is absorbed in a packed tower using 1.0 N (4 wt %) NaOH solution (E2, E3, P2, S4). An overall coefficient $K_G a$ is measured.

In this system, the liquid film is controlling but the gas film resistance is not negligible. The fast chemical reaction between NaOH and CO_2 takes place close to the interface, which gives a steeper concentration gradient for CO_2 in the water film. Hence, the value of $K_G a$ is much larger than for absorption of CO_2 in water. Because of this, these experimental values are not used to predict the absorption for other systems in towers.

These experimental results, however, can be used to compare the performances of various packings. To do this, the ratio f_p of $K_G a$ for a given packing to that for $1\frac{1}{2}$-in. Raschig rings at a liquid velocity G_x of 5000 $\text{lb}_\text{m}/\text{h}\cdot\text{ft}^2$ (6.782 $\text{kg/s}\cdot\text{m}^2$) and G_y of 1000 $\text{lb}_\text{m}/\text{h}\cdot\text{ft}^2$ (1.356 $\text{kg/s}\cdot\text{m}^2$) is obtained; these are given in Table 10.6-1. The f_p value is a relative ratio of the total interfacial areas, since the reaction of CO_2 in NaOH solution takes place in the relatively static holdup pools and in the dynamic holdup. Some f_p data have been obtained at $G_y = 500$ $\text{lb}_\text{m}/\text{h}\cdot\text{ft}^2$ instead of 1000 (E3). Eckert et al. (E2) showed that there is no effect of G_y in the range of 200–1000 $\text{lb}_\text{m}/\text{h}\cdot\text{ft}^2$ on the overall $K_G a$. This is expected where the liquid film resistance controls (S1). Values of f_p for various investigators agree within $\pm 10\%$ or less.

Predicting Mass-Transfer Film Coefficents

For estimating the performance $H_L(H_x)$ and $H_G(H_y)$ of a new packing, the values of f_p can be used to correct the experimental H_x values for oxygen absorption or desorption and the H_y value for NH_3 absorption with $1\frac{1}{2}$-in. Raschig rings. These values must also be corrected for Schmidt number, liquid viscosity, and flow rates.

1. Gas film coefficient H_y. Using the NH_3 absorption data corrected for the liquid film resistance of approximately 10%, H_G has been found to vary as G_y to an exponent between 0.3 and 0.4 (S1, T1) for values of G_y up to about 700 $lb_m/h \cdot ft^2$ (0.949 $kg/s \cdot m^2$). A value of 0.35 is used. For liquid flows of G_x from 500 to 5000 $lb_m/h \cdot ft^2$ (0.678–6.782 $kg/s \cdot m^2$), H_y varies as $G_x^{-0.4}$–$G_x^{-0.6}$, with the value of $G_x^{-0.5}$ used. Also, the value of H_y has been found to be proportional to $N_{Sc}^{0.5}$ of the gas phase. A value for H_y of 0.74 ft (0.226 m) is obtained from the correlation for $1\frac{1}{2}$-in. Raschig rings for the NH_3 system (S1) corrected for the small liquid film resistance of 10% at $G_x = 5000$ $lb_m/h \cdot ft^2$ (6.782 $kg/s \cdot m^2$) and $G_y = 500$ $lb_m/h \cdot ft^2$ (0.678 $kg/s \cdot m^2$). The value of $G_y = 500$ will be used instead of 1000, since there is no effect of G_y on f_p in this range. For the NH_3 system, $N_{Sc} = 0.66$ at 25°C. Then, for estimation of H_G for a new solute system and packing and flow rates of G_x and G_y using SI units,

$$H_G = H_y = \left(\frac{0.226}{f_p}\right)\left(\frac{N_{Sc}}{0.660}\right)^{0.5}\left(\frac{G_x}{6.782}\right)^{-0.5}\left(\frac{G_y}{0.678}\right)^{0.35} \quad \textbf{(10.8-1)}$$

where f_p for the new packing is given in Table 10.6-1 and H_G is in m.

2. Liquid film coefficient H_x. For gas flow rates up to loading or about 50% of the flooding velocity, the effect of G_y on H_x is small and can be neglected (S1). Using the oxygen desorption data, H_x is proportional to the liquid $N_{Sc}^{0.5}$. The $N_{Sc} = 372$ at 25°C for O_2 in water and the viscosity μ is 0.8937×10^{-3} $kg/m \cdot s$. Data for different packings show that H_x is proportional to (G_x/μ) to the 0.22–0.35 exponent, with an average of $(G_x/\mu)^{0.3}$. A value of $H_x = 1.17$ ft (0.357 m), where $G_x = 5000$ $lb_m/h \cdot ft^2$ is obtained from the correlation (S1) for the O_2 system and $1\frac{1}{2}$-in. Raschig rings. Then, to predict H_x for a new solute system and packing at velocities of G_x and G_y using SI units,

$$H_L = H_x = \left(\frac{0.357}{f_p}\right)\left(\frac{N_{Sc}}{372}\right)^{0.5}\left(\frac{G_x/\mu}{6.782/0.8937 \times 10^{-3}}\right)^{0.3} \quad \textbf{(10.8-2)}$$

These equations can be used for values of G_y up to almost 1000 $lb_m/h \cdot ft^2$ and G_x up to 5000 and remain below loading.

Correlations for Film Coefficients

The experimental data for the gas film coefficient in dilute mixtures have been correlated in terms of $H_G(= V/k'_y aS), H_L$. The empirical equation is as follows:

$$H_G(m) = \left(\frac{0.226}{f_p}\right)\left(\frac{N_{Sc}}{0.660}\right)^{0.5}\left(\frac{G_x}{6.782}\right)^{-0.5}\left(\frac{G_y}{0.678}\right)^{0.35}$$

$$H_L(m) = \left(\frac{0.357}{f_p}\right)\left(\frac{N_{Sc}}{372}\right)^{0.5}\left(\frac{G_x/\mu}{6.782/0.8937 \times 10^{-3}}\right)^{0.3}$$

where G's are total flows of L/G in kg per sec per square meter.

EXAMPLE 10.8-1. Prediction of Film Coefficients for CO_2 absorption

Predict H_G, H_L, H_{OL} for absorption of CO_2 from air by water in a dilute solution in a packed tower with 1.5 inch metal Pall rings at 303 K (30°C) and101.32 kPa pressure. The flow rates are $G_x = 4.069\ kg/s \cdot m^2$ and $G_y = 0.5424\ kg/s \cdot m^2$.

SOLUTION:

D_{AB} should be corrected for T= 303 K: $\mu = 1.86 \times 10^{-5}\ kg/m \cdot s\,; \rho = 1.166\ kg/m^3\,;$ $D_{AB} = 1.67 \times 10^{-5}\ m^2/s\,; @\ 303\ K$ $N_{Sc} = \frac{\mu}{\rho D_{AB}} = 0.958$ $H_G = \left(\frac{0.226}{f_p}\right)\left(\frac{N_{Sc}}{0.660}\right)^{0.5}\left(\frac{G_x}{6.782}\right)^{-0.5}\left(\frac{G_y}{0.678}\right)^{0.35}$ $= \left(\frac{0.226}{1.34}\right)\left(\frac{0.958}{0.660}\right)^{0.5}\left(\frac{4.069}{6.782}\right)^{-0.5}\left(\frac{0.5424}{0.678}\right)^{0.35}$ $= 0.2426\ m$	D_{AB} should be corrected for T= 303 K: $\mu = 0.8007 \times 10^{-3}\ kg/m \cdot s\,; \rho = 995.68\ kg/m^3\,;$ $D_{AB} = 2.0 \times 10^{-9}\ m^2/s\,; @\ 298\ K$ $\mu = 0.8937 \times 10^{-3}\ kg/m \cdot s; @298\ K$ $D_{AB} = 2.27 \times 10^{-9}\ m^2/s\,;$ corrected $@\ 303\ K$ $N_{Sc} = (\mu/\rho D_{AB}) = 354.3$ $H_L(m) = \left(\frac{0.357}{f_p}\right)\left(\frac{N_{Sc}}{372}\right)^{0.5}\left(\frac{G_x/\mu}{6.782/0.8937 \times 10^{-3}}\right)^{0.3}$ $= \left(\frac{0.357}{1.34}\right)\left(\frac{354.3}{372}\right)^{0.5}\left(\frac{4.069/0.8007 \times 10^{-3}}{6.782/0.8937 \times 10^{-3}}\right)^{0.3}$ $= 0.2306\ m$
$V = \frac{G_y}{MW} = \frac{0.5424}{28.97} = 0.01872\ \frac{kg\ mol}{s \cdot m^2}$	$L = \frac{G_x}{MW} = \frac{4.069}{18} = 0.2261\ \frac{kg\ mol}{s \cdot m^2}$

$$H_{OL} = H_L + \frac{L}{mV} H_G = 0.2306 + \left(\frac{0.2261}{1.86 \times 10^3 \times 0.01872}\right) 0.2426$$

$$= 0.2306\ (99.3\%\ for\ L - phase) + 0.001575 (0.7\%\ for\ G - phase) = 0.2322\ m$$

Since $m = 1.86 \times 10^3$ is very large (CO_2 is insoluble in water), the main resistance is in liquid phase. On the other hand, for the case of soluble gas like NH_3 ($m = 1.2$) at 303 K, the percent resistance in the gas pase will be about 90%

Correlations for Film Coefficients for Random Packings (Topic from Third Edition)

The experimental data for the gas film coefficient in dilute mixtures have been correlated in terms of $H_G\left(= V/k'_y aS\right)$. The empirical equation is as follows:

$$H_G = \alpha G_x^{\gamma} G_y^{\beta} N_{Sc}^{0.5}$$

where G's are total flows of L/G in kg per sec per square meter, while constants α, β, and γ for a packing as given in Table 10.8-1. The temperature effect, which is small, is included in the Schmidt number. Above equation can be used to correct existing data for absorption of solute A in a gas on a specific packing to absorption of solute E in the same system and the same mass-flow rates. This is done by Eq. (1 0.8-2).

$$H_{G(E)} = H_{G(A)}\left[N_{Sc(E)}/N_{Sc(A)}\right]^{0.5}$$

TABLE 10.8-1. *Gas Film Height of a Transfer Unit H_G in Meters**

				Range of Values	
Packing Type	α	β	γ	G_y	G_x
Raschig rings					
9.5 mm ($\frac{3}{8}$ in.)	0.620	0.45	−0.47	0.271–0.678	0.678–2.034
25.4 mm (1 in.)	0.557	0.32	−0.51	0.271–0.814	0.678–6.10
38.1 mm (1.5 in.)	0.830	0.38	−0.66	0.271–0.950	0.678–2.034
38.1 mm (1.5 in.)	0.689	0.38	−0.40	0.271–0.950	2.034–6.10
50.8 mm (2 in.)	0.894	0.41	−0.45	0.271–1.085	0.678–6.10
Berl saddles					
12.7 mm (0.5 in.)	0.541	0.30	−0.74	0.271–0.950	0.678–2.034
12.7 mm (0.5 in.)	0.367	0.30	−0.24	0.271–0.950	2.034–6.10
25.4 mm (1 in.)	0.461	0.36	−0.40	0.271–1.085	0.542–6.10
38.1 mm (1.5 in.)	0.652	0.32	−0.45	0.271–1.356	0.542–6.10

* $H_G = \alpha G_y^{\beta} G_x^{\gamma} N_{Sc}^{0.5}$, where G_y = kg total gas/s · m², G_x = kg total liquid/s · m², and $N_{Sc} = \mu/\rho D$.
Source: Data from Fellinger (P2) as given by R. E. Treybal, *Mass Transfer Operations.* New York: McGraw-Hill Book Company, 1955, p. 239. With permission.

The correlations for liquid film coefficients in dilute mixtures show that H_L is independent of gas rate until loading occurs, as given by (use SI units),

$$H_L = \theta\left(\frac{G_x}{\mu_L}\right)^{\eta} N_{Sc}^{0.5}$$

Data are given in Table 10.8-2 for different packings.

TABLE 10.8-2. *Liquid Film Height of a Transfer Unit H_L in Meters**

Packing	θ	η	*Range of G_x*
Raschig rings			
9.5 mm ($\frac{3}{8}$ in.)	3.21×10^{-4}	0.46	0.542–20.34
12.7 mm (0.5 in.)	7.18×10^{-4}	0.35	0.542–20.34
25.4 mm (1 in.)	2.35×10^{-3}	0.22	0.542–20.34
38.1 mm (1.5 in.)	2.61×10^{-3}	0.22	0.542–20.34
50.8 mm (2 in.)	2.93×10^{-3}	0.22	0.542–20.34
Berl saddles			
12.7 mm (0.5 in.)	1.456×10^{-3}	0.28	0.542–20.34
25.4 mm (1 in.)	1.285×10^{-3}	0.28	0.542–20.34
38.1 mm (1.5 in.)	1.366×10^{-3}	0.28	0.542–20.34

* $H_L = \theta(G_x/\mu_L)^\eta N_{Sc}^{0.5}$, where G_x = kg total liquid/s · m², μ_L = viscosity of liquid in kg/m · s, and $N_{Sc} = \mu_L/\rho D$. G_y is less than loading.

Prediction of Film Coefficients for Ammonia Absorption

Predict $H_G, H_L, K'_y a$ for absorption of NH_3 from water in a dilute solution in a packed tower with 25.4-mm Raschig rings at 303 K (86°F) and101.32 kPa pressure. The flow rates are $G_x = 2.543\ kg/s \cdot m^2$ and $G_y = 0.339\, kg/s \cdot m^2$.

SOLUTION:

Gas phase at T= 303 K: $\mu = 1.86 \times 10^{-5}\, kg/m \cdot s$; $\rho = 1.168\ kg/m^3$; $D_{AB} = 2.379 \times 10^{-5}\, m/s^2$; $N_{Sc} = \frac{\mu}{\rho D_{AB}} = 0.669$ $H_G = \alpha G_x^{\gamma} G_y^{\beta} N_{Sc}^{0.5}$ $= 0.57(0.557)^{0.32}(2.543)^{-0.51}(0.669)^{0.5}$ $= 0.200\, m$	Data for liquid including (D_{AB}) should be corrected for T= 303 K: $\mu = 0.8007 \times 10^{-3}\, kg/m \cdot s$; $\rho = 996\ kg/m^3$; $D_{AB} = 2.652 \times 10^{-9}\, m/s^2$; $N_{Sc} = \frac{\mu}{\rho D_{AB}} = 303.1$ $H_G = \theta \left(\frac{G_x}{\mu_L}\right)^{\eta} N_{Sc}^{0.5}$ $= 2.35 \times 10^{-3} \left(\frac{2.543}{0.8007 \times 10^{-3}}\right)^{0.22} (303.1)^{0.5}$ $= 0.2412\, m$
$k'_y a = \frac{V}{H_G S} = \frac{0.339/29}{0.200}$ $= 0.0584\ \frac{kg\ mol}{s \cdot m^3 \cdot mol\ frac}$	$k'_x a = \frac{L}{H_L S} = \frac{2.543/18}{0.2412} = 0.586\ \frac{kg\ mol}{s \cdot m^3 \cdot mol\ frac}$
$\frac{1}{K_y a} = \frac{1}{k_y a} + \frac{m'}{k_x a}$	$\frac{1}{K_y a} = \frac{1}{0.0584} + \frac{1.2}{0.586} = 17.12\ (89.3\%) + 2.48$ $= 19.168$ $K_y a = 0.0522 \frac{kg\ mol}{s \cdot m^3 \cdot mol\ frac}$