Example

A wetted wall absorption tower (2.54 cm diameter) is fed water and an ammonia-air mixture. At a particular level in the tower, the ammonia concentration in the bulk gas is 0.80 mole fraction and the mole fraction in the bulk liquid is 0.05. The temperature is 26.7 °C and the pressure is 1 atm. The rates of flow are such that the local mass transfer coefficient in the liquid is $k_L = 2.87 \times 10^{-5}$ kmol/m² s (kmol/m³). The local Sherwood number for the gas is 40. The diffusivity of ammonia in air is $2.297 \times 10^{-5}$ m²/s

Compute the local mass transfer flux for the ammonia absorption.
Illustration 5.1 A wetted-wall absorption tower, 1 in (2.54 cm) ID, is fed with water as the wall liquid and an ammonia-air mixture as the central-core gas. At a particular level in the tower, the ammonia concentration in the bulk gas is 0.80 mole fraction, that in the bulk liquid 0.05 mole fraction. The temperature = 80°F (26.7°C), the pressure 1 std atm. The rates of flow are such that the local mass-transfer coefficient in the liquid, from a correlation obtained with dilute solutions, is \( k_L = 0.34 \text{ mol/ft}^2 \cdot \text{h} \cdot \text{lb} \cdot \text{mol/ft}^2 \) = \( 2.87 \times 10^{-3} \text{ kmol/m}^2 \cdot \text{s} \cdot \text{kmol/m}^3 \), and the local Sherwood number for the gas is 40. The diffusivity of ammonia in air = 0.890 ft\(^2\)/h = \( 2.297 \times 10^{-5} \text{ m}^2/\text{s} \). Compute the local mass-transfer flux for the absorption of ammonia, ignoring the vaporization of water.

**Figure 5.5** Construction for Illustration 5.1.

**Solution** \( x_{A,G} = 0.80, \ x_{A,L} = 0.05 \) mole fraction ammonia. Because of the large concentration of ammonia in the gas, \( x_A \)'s rather than \( \bar{x}_A \)'s will be used. Notation is that of Chap. 3.

**Liquid** From Table 3.1, \( F_L = k_L x_{A,L} \). Since the molecular weight of ammonia and water are so nearly the same and the density of a dilute solution is practically that of water, the molar density \( c = 1000/18 = 55.5 \text{ kmol/m}^3 \). Since the \( k_L \) was determined for dilute solutions, where \( x_{A,L} \) is practically 1.0,

\[
F_L = (2.87 \times 10^{-3})(1.0)(55.5) = 1.590 \times 10^{-3} \text{ kmol/m}^2 \cdot \text{s}
\]

**Gas**

\[
Sh = \frac{F_G d}{c D_A} = 40
\]

\[
c = \frac{1}{22.41} = \frac{273}{273 + 26.7} = 0.04065 \text{ kmol/m}^3
\]

\[
D_A = 2.297 \times 10^{-5} \text{ m}^2/\text{s}
\]

\[
F_G = \frac{40 c D_A}{d} = \frac{40(0.04065)(2.297 \times 10^{-5})}{0.0254} = 1.471 \times 10^{-3} \text{ kmol/m}^2 \cdot \text{s}
\]

**Mass-transfer flux** The equilibrium-distribution data for ammonia are taken from those at 26.7°C in “The Chemical Engineers' Handbook,” 5th ed., p. 3-68:

<table>
<thead>
<tr>
<th>NH(_3) mole fraction ( x_A )</th>
<th>lb/( \text{ft}^2 )</th>
<th>N/( \text{m}^2 )</th>
<th>( \bar{x}_A )</th>
<th>( \frac{\bar{x}_A}{1.0133 \times 10^5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.41</td>
</tr>
<tr>
<td>0.05</td>
<td>1.04</td>
<td>7 171</td>
<td>0.0707</td>
<td>1.35</td>
</tr>
<tr>
<td>0.10</td>
<td>1.98</td>
<td>13 652</td>
<td>0.1347</td>
<td>2.85</td>
</tr>
<tr>
<td>0.25</td>
<td>8.69</td>
<td>59 917</td>
<td>0.591</td>
<td>3.07</td>
</tr>
<tr>
<td>0.30</td>
<td>13.52</td>
<td>93 220</td>
<td>0.920</td>
<td></td>
</tr>
</tbody>
</table>
These are plotted as the equilibrium curve in Fig. 5.5.

For transfer of only one component, \( N_A / \Sigma N = 1.0 \). Equation (5.21), with \( y_{A,i} \) and \( x_{A,i} \) replaced by \( y_A \) and \( x_A \), becomes

\[
y_A = 1 - (1 - y_A, o) \left( \frac{1 - x_{A,L}}{1 - x_A} \right)^{F_{L}/F_o} = 1 - (1 - 0.8) \left( \frac{1 - 0.05}{1 - x_A} \right)^{1.078}
\]

from which the following are computed:

<table>
<thead>
<tr>
<th>( x_A )</th>
<th>0.05</th>
<th>0.15</th>
<th>0.25</th>
<th>0.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y_A )</td>
<td>0.80</td>
<td>0.780</td>
<td>0.742</td>
<td>0.722</td>
</tr>
</tbody>
</table>

These are plotted as x's on Fig. 5.5, and the resulting curve intersects the equilibrium curve to give the interface compositions, \( x_{A,i} = 0.274, y_{A,i} = 0.732 \). Therefore Eq. (5.20) provides

\[
N_A = \frac{1(1.590 \times 10^{-3})}{\ln \frac{1 - 0.05}{1 - 0.274}} \frac{1 - 0.732}{1 - 0.80} = 4.30 \times 10^{-4} \text{ kmol NH}_3 \text{ absorbed/m}^2 \cdot \text{s, local flux} \text{ Ans.}
\]

Overall coefficient: Although it is not particularly useful in this case, the overall coefficient will be computed to demonstrate the method. The gas concentration in equilibrium with the bulk liquid (\( x_{A,L} = 0.05 \) is, from Fig. 5.5, \( y_A = 0.0707 \). The chord slope \( m' \) is therefore

\[
m' = \frac{y_{A,i} - y_A}{x_{A,i} - x_{A,L}} = \frac{0.732 - 0.0707}{0.274 - 0.05} = 2.95
\]

Note that unless the equilibrium curve is straight, this cannot be obtained without first obtaining \( y_{A,i} \) for \( x_{A,i} \), which case there is no need for the overall coefficient. In Eq. (5.25), normally we would obtain \( F_{DG} \) by trial, by assuming \( N_A \). Thus (with an eye on the answer obtained above), assume \( N_A = 4.30 \times 10^{-4} \). Then Eq. (5.25) becomes

\[
\frac{e^{4.30 \times 10^{-4}}}{F_{DG}} = e^{(4.30 \times 10^{-4})(1.47 \times 10^{-3}) + 2.95 \left( \frac{1 - 0.05}{1 - 0.80} \right)} \left( 1 - e^{-4.30 \times 10^{-4}(1.590 \times 10^{-3})} \right) = 4.66
\]

\[
F_{DG} = 2.78 \times 10^{-4} \text{ kmol/m}^2 \cdot \text{s}
\]

As a check of the trial value of \( N_A \), Eq. (5.22) is

\[
N_A = 1(2.78 \times 10^{-4}) \ln \frac{1 - 0.0707}{1 - 0.80} = 4.30 \times 10^{-4} \text{ (check)}
\]

Use of \( k \)-type coefficients: There are, of course, \( k \)'s which are consistent with the \( F \)'s and which will produce the correct result. Thus, \( k_f = F_{DG} / \overline{F}_{R,M} = 6.29 \times 10^{-3} \) and \( k_g = F_L / \overline{F}_{R,M} = 1.885 \times 10^{-3} \) will produce the same result as above. But these \( k \)'s are specific for the concentration levels at hand, and the \( \overline{F}_{R,M} \) and \( x_{R,M} \) terms, which correct for the bulk-flow flux (the \( N_A \) term of Eq. (2.4), cannot be obtained until \( x_{A,i} \) and \( y_{A,i} \) are first obtained as above.

However, if it had been assumed that the concentrations were dilute and that the bulk-flow terms were negligible, the Sherwood number might have been (incorrectly) interpreted as

\[
Sh = \frac{k_f R T d}{\mu D_A} = 40 \frac{k_f(8314)(273.2 + 26.7)(0.0254)}{(1.0133 \times 10^{6})(2.297 \times 10^{-5})} = 1.47 \times 10^{-3} \text{ kmol/m}^2 \cdot \text{s} \cdot \text{(mole fraction)}
\]

and, in the case of the liquid,

\[
k_g = k_c = (2.67 \times 10^{-3})(5.5) = 1.59 \times 10^{-3} \text{ kmol/m}^2 \cdot \text{s} \cdot \text{(mole fraction)}
\]

These \( k \)'s are suitable for small driving forces but are unsuitable here. Thus

\[
\frac{k_f}{k_g} = \frac{1.59 \times 10^{-3}}{1.47 \times 10^{-3}} = -1.08
\]

and a line of this slope (the dashed line in Fig. 5.5) drawn from \((x_{A,L}, y_{A,L})\) intersects the equilibrium curve at \((x_A = 0.250, y_A = 0.585)\). If this is interpreted to be \((x_{A,i}, y_{A,i})\), the calculated flux would be

\[
N_A = k_s(x_{A,i} - x_{A,L}) = (1.59 \times 10^{-3})(0.250 - 0.05) = 3.17 \times 10^{-4}
\]

or

\[
N_A = k_g(y_{A,o} - y_{A,i}) = (1.47 \times 10^{-3})(0.8 - 0.585) = 3.17 \times 10^{-4}
\]

The corresponding overall coefficient, with \( m' = (0.585 - 0.0707)/(0.250 - 0.05) = 2.57 \), would be

\[
\frac{1}{k_f} \frac{1}{k_g} + m' \frac{1}{k_s} = \frac{1}{1.59 \times 10^{-3}} + \frac{2.57}{1.47 \times 10^{-3}} + \frac{2.57}{1.59 \times 10^{-3}}
\]

\[
F_{DG} = 4.35 \times 10^{-4} \text{ kmol/m}^2 \cdot \text{s, mole fraction}
\]

\[
N_A = k_f(y_{A,o} - y_{A,i}) = (4.35 \times 10^{-4})(0.8 - 0.0707) = 3.17 \times 10^{-4}
\]
Concentrated Solution

\[ F_G = 1.471 \times 10^{-3} \]
\[ F_L = 1.590 \times 10^{-3} \]
\[ N_A = 4.30 \times 10^{-4} \]
\[ k_G = 6.29 \times 10^{-3} \]
\[ k_L = 1.885 \times 10^{-3} \]

Assumed Dilute Solution

\[ k_G = 1.471 \times 10^{-3} \]
\[ k_L = 1.590 \times 10^{-3} \]
\[ N_A = 3.17 \times 10^{-4} \]

\[ N_A = 4.30 \times 10^{-4} \]