Figure 1: Equilibrium Single-stage Contacting

Gas out
V_1, y_1

Single-Stage Equil.
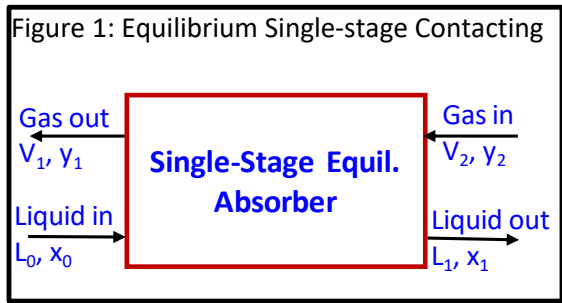Absorber

Gas in
V_2, y_2

Liquid in
L_0, x_0

Liquid out
L_1, x_1

In a liquid-gas contacting, it is desired to remove solute A from a gas mixture with the help of liquid solvent using the separation process of absorption. The solute A is transferred from the gas phase to the liquid phase. A single stage equilibrium counter-current contacting is shown in the adjoining figure, where V and L are molar flowrates of the gas phase and liquid phase, respectively. Also, x and y are mole fractions of solute A in the liquid stream and the gas stream, respectively. Note that the Henry's law, $P_A = Hx_A$, states that partial pressure varies linearly with x_A. Given

$$T = 298 \ K, P = 1.0 \ atm, H = 2.0 \ \frac{atm}{mol}, y_2 = 0.10, x_0 = 0.01, V_2 = 5 \ \frac{kg \ mol}{h}, L_0 = 10 \ \frac{kg \ mol}{h}$$

Choose the best possible answer from the following

(1)

(a) $x_1 = 0.0$	(b) $x_1 = 0.01$
(c) $x_1 = 0.009$	(d) $x_1 = 0.03$

(2)

(a) $y_1 = 0.0$	(b) $y_1 = 0.009$
(c) $y_1 = 0.10$	(d) $y_1 = 0.06$

(3)

(a) $L_1 = 10.2, V_1 = 4.8$	(b) $L_1 = 10.0, V_1 = 5.0$
(c) $L_1 = 9.8, V_1 = 5.2$	(d) $L_1 = 12.0, V_1 = 5$

(4) If the temperature is increased, then one could have

(a) $H = 1.0$	(b) $H = 1.8$
(c) $H = 2.0$	(d) $H = 2.2$

(5) If the pressure is increased to 2 atm, then one could have

(a) solubility of A will increase in the solvent	(b) solubility of A will decrease in the solvent
(c) solubility of A will be unaffected	(d) partial pressure of A will increase in the gas phase

(6) The Knudsen diffusivity of a gas depends upon
(i) temperature (ii) pressure (iii) molecular weight (iv) capillary radius

(a) (i), (ii) and (iii) are correct	(b) (i), (iii) and (iv) are correct
(c) (i), (ii), (iii) and (iv) are correct	(d) (ii), (iii) and (iv) are correct

(7) The Knudsen diffusion coefficient will be lowest for

(a) hydrogen (MW = 2)	(b) nitrogen (MW = 28)
(c) helium (MW = 4)	(d) argon(MW = 40)

(8) If the solute A is nearly insoluble in the liquid phase, this means that the equilibrium constant (m) represented by $y = mx$ is
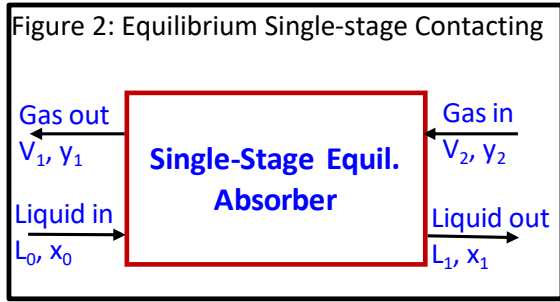
(a) very high	(b) high
(c) low	(d) very low

(9) In multi-stage absorber design, thermodynamic solubility data are needed for plotting

(a) the equilibrium line only	(b) the operating line only
(c) both operating and equilibrium lines	(d) No need of such data in the design

(10) In the multi-stage absorber design, (L/V) ratio affects the slope of

(a) the equilibrium line only	(b) the operating line only
(c) both operating and equilibrium lines	(d) No effect on the slope

1	2	3	4	5	6	7	8	9	10

Figure 2: Equilibrium Single-stage Contacting

Gas out
V_1, y_1

Single-Stage Equil. Absorber

Gas in
V_2, y_2

Liquid in
L_0, x_0

Liquid out
L_1, x_1

In a liquid-gas contacting, it is desired to remove solute A from a gas mixture with the help of liquid solvent using the separation process of absorption. The solute A is transferred from the gas phase to the liquid phase. A single stage equilibrium counter-current contacting is shown in the adjoining figure, where V and L are molar flowrates of the gas phase and liquid phase, respectively. Also, x and y are mole fractions of solute A in the liquid stream and the gas stream, respectively. Note that the Henry's law, $P_A = Hx_A$, states that partial pressure varies linearly with x_A. Given

$$T = 298\ K, P = 1.0\ atm, H = 2.0\ \frac{atm}{mol}, y_2 = 0.10, x_0 = 0.01, V_2 = 5\ \frac{kg\ mol}{h}, L_0 = 10\ \frac{kg\ mol}{h}$$

Choose the best possible answer from the following

(1)

(a) $x_1 = 0.03$	(b) $x_1 = 0.01$
(c) $x_1 = 0.009$	(d) $x_1 = 0.00$

(2)

(a) $y_1 = 0.06$	(b) $y_1 = 0.009$
(c) $y_1 = 0.10$	(d) $y_1 = 0.00$

(3)

(a) $L_1 = 10.2, V_1 = 4.8$	(b) $L_1 = 10.0, V_1 = 5.0$
(c) $L_1 = 9.8, V_1 = 5.2$	(d) $L_1 = 12.0, V_1 = 5$

(4) If the temperature is increased, then one could have

(a) $H = 2.2$	(b) $H = 2.0$
(c) $H = 1.8$	(d) $H = 1.0$

(5) If the pressure is increased to 2 atm, then one could have

(a) solubility of A will decrease in the solvent	(b) solubility of A will increase in the solvent
(c) solubility of A will be unaffected	(d) partial pressure of A will increase in gas phase

(6) The Knudsen diffusivity of a gas depends upon
(i) pressure (ii) temperature (iii) molecular weight (iv) capillary radius

(a) (i), (ii) and (iii) are correct	(b) (i), (iii) and (iv) are correct
(c) (i), (ii), (iii) and (iv) are correct	(d) (ii), (iii) and (iv) are correct

(7) The Knudsen diffusion coefficient will be lowest for

(a) argon(MW = 40)	(b) nitrogen (MW = 28)
(c) helium (MW = 4)	(d) hydrogen (MW = 2)

(8) If the solute A is nearly insoluble in the liquid phase, this means that the equilibrium constant (m) represented by $y = mx$ is
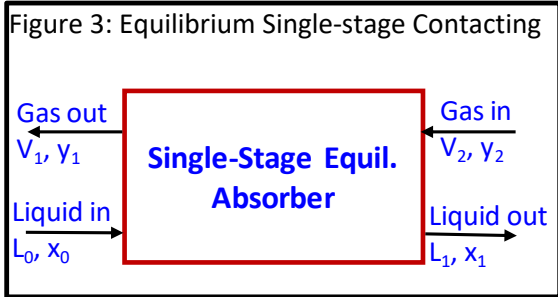
(a) very low	(b) high
(c) low	(d) very high

(9) In multi-stage absorber design, thermodynamic solubility data are needed for plotting

(a) the operating line only	(b) the equilibrium line only
(c) both operating and equilibrium lines	(d) No need of such data in the design

Roll Number:

(10) In the multi-stage absorber design, (L/V) ratio affects the slope of

| (a the operating line only | (b)) the equilibrium line only |
| (c) both operating and equilibrium lines | (d) No effect on the slope |

1	2	3	4	5	6	7	8	9	10

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┌─────────────────────────────────────────────────┐
│ Figure 3: Equilibrium Single-stage Contacting    │
│                                                   │
│  Gas out          ┌──────────────┐   Gas in       │
│  V₁, y₁    ◄───── │ Single-Stage  │ ◄──  V₂, y₂    │
│                   │ Equil.        │                │
│                   │ Absorber      │                │
│  Liquid in ─────► │               │ ──► Liquid out │
│  L₀, x₀           └──────────────┘     L₁, x₁      │
└─────────────────────────────────────────────────┘
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Figure 3: Equilibrium Single-stage Contacting

Gas out V_1, y_1 — **Single-Stage Equil. Absorber** — Gas in V_2, y_2

Liquid in L_0, x_0 — Liquid out L_1, x_1

In a liquid-gas contacting, it is desired to remove solute A from a gas mixture with the help of liquid solvent using the separation process of absorption. The solute A is transferred from the gas phase to the liquid phase. A single stage equilibrium counter-current contacting is shown in the adjoining figure, where V and L are molar flowrates of the gas phase and liquid phase, respectively. Also, x and y are mole fractions of solute A in the liquid stream and the gas stream, respectively. Note that the Henry's law, $P_A = Hx_A$, states that partial pressure varies linearly with x_A. Given

$$T = 298\ K, P = 1.0\ atm, H = 2.0\ \frac{atm}{mol}, y_2 = 0.10, x_0 = 0.01, V_2 = 5\ \frac{kg\ mol}{h}, L_0 = 10\ \frac{kg\ mol}{h}$$

Choose the best possible answer from the following

(1)

(a) $y_1 = 0.06$	(b) $y_1 = 0.009$
(c) $y_1 = 0.10$	(d) $y_1 = 0.00$

(2)

(a) $x_1 = 0.03$	(b) $x_1 = 0.01$
(c) $x_1 = 0.009$	(d) $x_1 = 0.00$

(3)

(a) $L_1 = 10.2, V_1 = 4.8$	(b) $L_1 = 10.0, V_1 = 5.0$
(c) $L_1 = 9.8, V_1 = 5.2$	(d) $L_1 = 12.0, V_1 = 5$

(4) If the temperature is increased, then one could have

(a) $H = 2.0$	(b) $H = 2.2$
(c) $H = 1.8$	(d) $H = 1.0$

(5) If the pressure is increased to 2 atm, then one could have

(a) solubility of A will decrease in the solvent	(b) solubility of A will increase in the solvent
(c) solubility of A will be unaffected	(d) partial pressure of A will increase in gas phase

(6) The Knudsen diffusivity of a gas depends upon
(i) temperature (ii) molecular weight (iii) capillary radius (iv) pressure

(a) (i), (ii) and (iii) are correct	(b) (i), (iii) and (iv) are correct
(c) (i), (ii), (iii) and (iv) are correct	(d) (ii), (iii) and (iv) are correct

(7) The Knudsen diffusion coefficient will be lowest for

(a) argon(MW = 40)	(b) nitrogen (MW = 28)
(c) helium (MW = 4)	(d) hydrogen (MW = 2)

(8) If the solute A is nearly insoluble in the liquid phase, this means that the equilibrium constant (m) represented by $y = mx$ is

(a) very low	(b) high
(c) low	(d) very high

(9) In multi-stage absorber design, thermodynamic solubility data are needed for plotting

(a) both operating and equilibrium lines	(b) the operating line only
(c) the equilibrium line only	(d) No need of such data in the design

(10) In the multi-stage absorber design, (L/V) ratio affects the slope of

(a) both operating and equilibrium lines	(b) the operating line only
(c) the equilibrium line only	(d) No effect on the slope

1	2	3	4	5	6	7	8	9	10

Mass Transfer Operations (CHE 318)

Test 2: March 11, 2019 (Time: 75 min)

- **Open book examination (Carry out detailed calculations in answer sheet)**

Question 1:

At 358 K, ammonia gas *(A)* is diffusing at steady state through an inert, non-diffusing mixture of nitrogen *(B)* and hydrogen *(C)*. The mole fraction at $z_1 = 0$ are $x_{A1} = 0.8$, $x_{B1} = 0.15$ and $x_{C1} = 0.05$; and at $z_2 = 10.0$ mm, $x_{A2} = 0.2$, $x_{B2} = 0.6$ and $x_{C2} = 0.2$.

The diffusivities <u>at 358 K and 101.3 kPa</u> are $D_{AB} = 3.28 \times 10^{-5}$ m^2/s and $D_{AC} = 1.093 \times 10^{-4}$ m^2/s.

Calculate the flux of ammonia at a total pressure of 10.13 kPa (0.1 atm)

$z_1 = 0$; $x_{A1} = 0.80$, $x_{B1} = 0.15$, $x_{C1} = 0.05$

$z_2 = 10.0$ mm; $x_{A2} = 0.20$, $x_{B2} = 0.60$, $x_{C2} = 0.20$

$z_1 = 0$; $x'_{B1} = 0.75$, $x'_{C1} = 0.25$

$z_2 = 10.0$ mm; $x'_{B2} = 0.75$, $x'_{C2} = 0.25$

At P =0.1 atm;

$$D_{Am} = \left[\frac{x'_B}{D_{AB}} + \frac{x'_C}{D_{AC}} \right]^{-1} = \left[\frac{0.75}{3.28 \times 10^{-4}} + \frac{0.25}{1.093 \times 10^{-4}} \right] = 3.95 \times 10^{-4} \frac{m^2}{s}$$

$$x_{A1} = 0.80; \ x_{A2} = 0.20$$

$$p_{A1} = 0.080 \ atm; \ p_{A2} = 0.020 \ atm$$

$$p_{i1} = P - p_{A1} = 0.020 \ atm; \ p_{i2} = P - p_{A2} = 0.080 \ atm$$

$$p_{iM} = \frac{p_{i2} - p_{i1}}{\ln(p_{i2}/p_{i2})} = \frac{0.08 - 0.02}{\ln(0.08/0.02)} = 0.0433 \ atm$$

$$N_A = \frac{D_{Am}P}{RT(z_2 - z_1)p_{iM}}(p_{A1} - p_{A2})$$

$$= \frac{(3.95 \times 10^{-4})(1)}{82.06 \times 358 \times (0.01 \times 10^{-3} - 0) \times 0.0433}(0.08 - 0.02)$$

$$= 1.87 \times 10^{-4} \frac{kg \ mol}{m^2 s}$$

Question-2:

Mercury at 26.5 C is flowing through a packed bed of lead spheres having a diameter of 2.096 mm with a void fraction of 0.499. The superficial velocity is 0.020 m/s. The solubility of lead in mercury is 1.7 mol %, the Schmidt number is 124.1. Use viscosity of solution as µ = 1.577 ×10⁻³ Pa·s, and density, $\rho = 13530 \ (kg/m^3)$.

- Determine the Reynolds number (N_{Re})
- Determine the j-factor for mass transfer, $J_D = \frac{k'_c}{v}(N_{Sc})^{2/3} = \frac{N_{Sh}}{N_{Re}N_{Sc}^{1/3}}$
- Determine the mass transfer coefficient, $k'_c, m/s$
- Predict the value of the mass transfer coefficient for the case of A diffusing through non-diffusing B.
- Determine the diffusivities of mercury in lead (if possible) and lead in mercury (if possible)

$$N_{Re} = \left(\frac{Dv\rho}{\mu}\right) = \left(\frac{2.096 \times 10^{-3} \times 0.02 \times 13530}{1.577 \times 10^{-3}}\right) = 359.6$$

$$N_{Sc} = \frac{(\mu/\rho)}{D_{AB}} = 124.1$$

For packed beds, $N_{Re} = 55 - 1500$

$$J_D = \frac{0.250}{\varepsilon} N_{Re}^{-0.31} = \frac{0.250}{0.499}(359.6)^{-0.31} = 0.08082$$

$$J_D = \frac{k'_c}{v}(N_{Sc})^{2/3}$$

$$k'_c = \frac{J_D}{(N_{Sc})^{2/3}} v = 6.49 \times 10^{-5} \ m/s$$

$$k_c = \frac{k'_c}{x_{BM}} = 6.5 \times 10^{-5}\left(\frac{\ln\left(\frac{1-0}{1-0.017}\right)}{(1-0)-(1-0.017)}\right) = \frac{6.5 \times 10^{-5}}{0.99}$$

$$= 6.55 \times 10^{-5}$$

For lead in mercury, the molecular diffusivity can be given as

$$D_{AB} = \frac{(\mu/\rho)}{N_{Sc}} = \left(\frac{1.577 \times 10^{-3}/13530}{124.1}\right) = 9.4 \times 10^{-10} \frac{m^2}{s}$$

Determination of mercury in lead is not possible since $D_{AB} \neq D_{BA}$ for liquid phase

Question-3:

A mixture of He (A, MW = 4) and Ar (B, MW = 40) is diffusing through a capillary having a radius of 100Å and length 0.01 mm at 298 K and a total pressure of 1.013 ×10⁶ Pa (10 atm)

- Calculate the Knudsen diffusivities of He (A) and Ar (B) and compare with the molecular diffusivity D_{AB}
- Predict the steady state flux N_A if x_{A1} =0.5 and x_{A2} = 0.0 using Eqn (7.6-18) and Eqn (7.6-12).
  - Without making any calculations, predict whether the steady-state flux (N_A) will increase or decrease if the total pressure is decreased. Explain clearly with reasons.

- Knudsen diffusivity (D_{KA}) of He *(A)*.

$$D_{KA} = 97\bar{r}\sqrt{\frac{T}{M_A}} = 97 \times 100 \times 10^{-10}\sqrt{\frac{298}{4}} = 8.37 \times 10^{-6} \; m^2/s$$

- Knudsen diffusivity (D_{KB}) of Ar *(B)*.

$$D_{KB} = 97\bar{r}\sqrt{\frac{T}{M_A}} = 97 \times 100 \times 10^{-10}\sqrt{\frac{298}{40}} = 2.65 \times 10^{-6} \; m^2/s$$

- Molecular diffusivity (D_{AB}) at 10 atm using data from Table at 1 atm. Therefore,

$$D_{AB} = \frac{7.29 \times 10^{-5}}{10} = 7.29 \times 10^{-6} \; m^2/s$$

- Predict the steady state flux N_A if x_{A1} =0.5 and x_{A2} = 0.0 using Eqn (7.6-18) and Eqn (7.6-12).

$$\alpha = 1 - \left(\frac{M_A}{M_B}\right)^{0.5} = 1 - \left(\frac{4}{40}\right)^{0.5} = 0.684$$

$$N_A = \frac{D_{AB}P}{\alpha RTL} ln \frac{1 - \alpha x_{A2} + D_{AB}/D_{KA}}{1 - \alpha x_{A1} + D_{AB}/D_{KA}}$$

$$= \frac{7.29 \times 10^{-6}}{0.684 \times 8314 \times 298} \frac{1.01325 \times 10^6}{(0.01/1000)} ln \frac{1 - 0.684 \times 0.0 + 7.29 \times 10^{-6}/8.37 \times 10^{-6}}{1 - 0.684 \times 0.5 + 7.29 \times 10^{-6}/8.37 \times 10^{-6}}$$

$$= \mathbf{8.8 \times 10^{-2}} kg \; mol \; A/s \cdot m^2$$

Values of D_{KA} and D_{AB} are comparable. Therefore, the diffusion takes place in transition region. Here, N_A will depend on pressure. Any decrease in P will decrease the flux.