Chapter 14
MASS TRANSFER

Mass Transfer and Analogy Between Heat and Mass Transfer

14-1C *Bulk fluid flow* refers to the transportation of a fluid on a macroscopic level from one location to another in a flow section by a mover such as a fan or a pump. *Mass flow* requires the presence of two regions at different chemical compositions, and it refers to the movement of a chemical species from a high concentration region towards a lower concentration one relative to the other chemical species present in the medium. Mass transfer cannot occur in a homogeneous medium.

14-2C The *concentration* of a commodity is defined as the amount of that commodity per unit volume. The *concentration gradient dC/dx* is defined as the change in the concentration C of a commodity per unit length in the direction of flow x. The *diffusion rate* of the commodity is expressed as

$$\dot{Q} = -k_{\text{diff}} A \frac{dC}{dx}$$

where A is the area normal to the direction of flow and k_{diff} is the *diffusion coefficient* of the medium, which is a measure of how fast a commodity diffuses in the medium.

14-3C Examples of different kinds of diffusion processes:

(a) *Liquid-to-gas*: A gallon of gasoline left in an open area will eventually evaporate and diffuse into air.

(b) *Solid-to-liquid*: A spoon of sugar in a cup of tea will eventually dissolve and move up.

(c) *Solid-to gas*: A moth ball left in a closet will sublimate and diffuse into the air.

(d) *Gas-to-liquid*: Air dissolves in water.

14-4C Although heat and mass can be converted to each other, there is no such a thing as “mass radiation”, and mass transfer cannot be studied using the laws of radiation transfer. Mass transfer is analogous to conduction, but it is not analogous to radiation.

14-5C (*a*) *Temperature difference* is the driving force for heat transfer, (*b*) *voltage difference* is the driving force for electric current flow, and (*c*) *concentration difference* is the driving force for mass transfer.

14-6C (*a*) *Homogenous reactions* in mass transfer represent the generation of a species within the medium. Such reactions are analogous to internal heat generation in heat transfer. (*b*) *Heterogeneous reactions* in mass transfer represent the generation of a species at the surface as a result of chemical reactions occurring at the surface. Such reactions are analogous to specified surface heat flux in heat transfer.

Mass Diffusion

14-7C In the relation $\dot{Q} = -kA(dT/dx)$, the quantities $\dot{Q}$, *k*, *A*, and *T* represent the following in heat conduction and mass diffusion:

$\dot{Q}$ = Rate of heat transfer in heat conduction, and rate of mass transfer in mass diffusion.

k = Thermal conductivity in heat conduction, and mass diffusivity in mass diffusion.

A = Area normal to the direction of flow in both heat and mass transfer.

T = Temperature in heat conduction, and concentration in mass diffusion.

14-8C (*a*) T (*b*) F (*c*) F (*d*) T (*e*) F

14-9C (*a*) T (*b*) F (*c*) F (*d*) T (*e*) T

14-10C In the Fick's law of diffusion relations expressed as $\dot{m}_{\text{diff,A}} = -\rho A D_{\text{AB}} \dfrac{dw_{\text{A}}}{dx}$ and $\dot{N}_{\text{diff,A}} = -CAD_{\text{AB}} \dfrac{dy_{\text{A}}}{dx}$, the diffusion coefficients D_{AB} are the same.

14-11C The mass diffusivity of a gas mixture (*a*) increases with increasing temperature and (*a*) decreases with increasing pressure.

14-12C In a binary ideal gas mixture of species A and B, the diffusion coefficient of A in B is equal to the diffusion coefficient of B in A. Therefore, the mass diffusivity of air in water vapor will be equal to the mass diffusivity of water vapor in air since the air and water vapor mixture can be treated as ideal gases.

14-13C Solids, in general, have different diffusivities in each other. At a given temperature and pressure, the mass diffusivity of copper in aluminum will not be the equal to the mass diffusivity of aluminum in copper.

14-14C We would carry out the hardening process of steel by carbon at high temperature since mass diffusivity increases with temperature, and thus the hardening process will be completed in a short time.

14-15C The molecular weights of CO_2 and N_2O gases are the same (both are 44). Therefore, the mass and mole fractions of each of these two gases in a gas mixture will be the same.

14-16 The molar fractions of the constituents of moist air are given. The mass fractions of the constituents are to be determined.

Assumptions The small amounts of gases in air are ignored, and dry air is assumed to consist of N_2 and O_2 only.

Properties The molar masses of N_2, O_2, and H_2O are 28.0, 32.0, and 18.0 kg/kmol, respectively (Table A-1)

Analysis The molar mass of moist air is determined to be

$$M = \sum y_i M_i = 0.78 \times 28.0 + 0.20 \times 32.0 + 0.02 \times 18 = 28.6 \text{ kg / kmol}$$

Then the mass fractions of constituent gases are determined from Eq. 14-10 to be

Moist air
78% N_2
20% O_2
2% H_2 O
(Mole fractions)

N_2: $$w_{N_2} = y_{N_2} \frac{M_{N_2}}{M} = (0.78)\frac{28.0}{28.6} = \mathbf{0.764}$$

O_2: $$w_{O_2} = y_{O_2} \frac{M_{O_2}}{M} = (0.20)\frac{32.0}{28.6} = \mathbf{0.224}$$

H_2O: $$w_{H_2O} = y_{H_2O} \frac{M_{H_2O}}{M} = (0.02)\frac{18.0}{28.6} = \mathbf{0.012}$$

Therefore, the mass fractions of N_2, O_2, and H_2O in dry air are 76.4%, 22.4%, and 1.2%, respectively.

14-17E The masses of the constituents of a gas mixture are given. The mass fractions, mole fractions, and the molar mass of the mixture are to be determined.

Assumptions None.

Properties The molar masses of N_2, O_2, and CO_2 are 28, 32, and 44 lbm/lbmol, respectively (Table A-1)

Analysis (*a*) The total mass of the gas mixture is determined to be

$$m = \sum m_i = m_{O_2} + m_{N_2} + m_{CO_2} = 5 + 8 + 10 = 23 \text{ lbm}$$

5 lbm O_2
8 lbm N_2
10 lbm CO_2

Then the mass fractions of constituent gases are determined to be

N_2: $$w_{N_2} = \frac{m_{N_2}}{m} = \frac{8}{23} = \mathbf{0.348}$$

O_2: $$w_{O_2} = \frac{m_{O_2}}{m} = \frac{5}{23} = \mathbf{0.217}$$

CO_2: $$w_{CO_2} = \frac{m_{CO_2}}{m} = \frac{10}{23} = \mathbf{0.435}$$

(*b*) To find the mole fractions, we need to determine the mole numbers of each component first,

N_2: $$N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{8 \text{ lbm}}{28 \text{ lbm / lbmol}} = \mathbf{0.286 \text{ lbmol}}$$

O_2: $$N_{O_2} = \frac{m_{O_2}}{M_{O_2}} = \frac{5 \text{ lbm}}{32 \text{ lbm / lbmol}} = \mathbf{0.156 \text{ lbmol}}$$

CO_2: $$N_{CO_2} = \frac{m_{CO_2}}{M_{CO_2}} = \frac{10 \text{ lbm}}{44 \text{ lbm / lbmol}} = \mathbf{0.227 \text{ lbmol}}$$

Thus,

$$N_m = \sum N_i = N_{N_2} + N_{O_2} + N_{CO_2} = 0.286 + 0.156 + 0.227 = 0.669 \text{ lbmol}$$

Then the mole fraction of gases are determined to be

N_2: $$y_{N_2} = \frac{N_{N_2}}{N_m} = \frac{0.2868}{0.669} = \mathbf{0.428}$$

O_2: $$y_{O_2} = \frac{N_{O_2}}{N_m} = \frac{0.156}{0.669} = \mathbf{0.233}$$

CO_2: $$y_{CO_2} = \frac{N_{CO_2}}{N_m} = \frac{0.227}{0.669} = \mathbf{0.339}$$

(*c*) The molar mass of the mixture is determined from

$$M = \frac{m_m}{N_m} = \frac{23 \text{ lbm}}{0.669 \text{ lbmol}} = \mathbf{34.4 \text{ lbm / lbmol}}$$

14-18 The mole fractions of the constituents of a gas mixture are given. The mass of each gas and the molar mass of the mixture are to be determined.

Assumptions None.

Properties The molar masses of H_2 and N_2 are 2.0 and 28.0 kg/kmol, respectively (Table A-1)

Analysis The mass of each gas is

H_2: $$m_{H_2} = N_{H_2} M_{H_2} = (8 \text{ kmol}) \times (2 \text{ kg/kmol}) = \mathbf{16 \ kg}$$

N_2: $$m_{N_2} = N_{N_2} M_{N_2} = 2 \text{ kmol}) \times (28 \text{ kg/kmol}) = \mathbf{56 \ kg}$$

8 kmol H_2
2 kmol N_2

The molar mass of the mixture and its apparent gas constant are determined to be

$$M = \frac{m_m}{N_m} = \frac{16+56 \text{ kg}}{8+2 \text{ kmol}} = 7.2 \ \text{kg/kmol}$$

$$R = \frac{R_u}{M} = \frac{8.314 \text{ kJ/kmol}\cdot\text{K}}{7.2 \text{ kg/kmol}} = \mathbf{1.15 \ kJ/kg\cdot K}$$

14-19 The mole numbers of the constituents of a gas mixture at a specified pressure and temperature are given. The mass fractions and the partial pressures of the constituents are to be determined.

Assumptions The gases behave as ideal gases.

Properties The molar masses of N_2, O_2 and CO_2 are 28, 32, and 44 kg/kmol, respectively (Table A-1)

Analysis When the mole fractions of a gas mixture are known, the mass fractions can be determined from

$$w_i = \frac{m_i}{m_m} = \frac{N_i M_i}{N_m M_m} = y_i \frac{M_i}{M_m}$$

The apparent molar mass of the mixture is

$$M = \sum y_i M_i = 0.65\times 28.0 + 0.20\times 32.0 + 0.15\times 44.0 = 31.2 \ \text{kg/kmol}$$

Then the mass fractions of the gases are determined from

N_2: $$w_{N_2} = y_{N_2}\frac{M_{N_2}}{M} = (0.65)\frac{28.0}{31.2} = \mathbf{0.583} \quad \text{(or 58.3\%)}$$

O_2: $$w_{O_2} = y_{O_2}\frac{M_{O_2}}{M} = (0.20)\frac{32.0}{31.2} = \mathbf{0.205} \quad \text{(or 20.5\%)}$$

CO_2: $$w_{CO_2} = y_{CO_2}\frac{M_{CO_2}}{M_m} = (0.15)\frac{44}{31.2} = \mathbf{0.212} \quad \text{(or 21.2\%)}$$

65% N_2
20% O_2
15% CO_2
290 K
250 kPa

Noting that the total pressure of the mixture is 250 kPa and the pressure fractions in an ideal gas mixture are equal to the mole fractions, the partial pressures of the individual gases become

$$P_{N_2} = y_{N_2} P = (0.65)(250 \text{ kPa}) = \mathbf{162.5 \ kPa}$$

$$P_{O_2} = y_{O_2} P = (0.20)(250 \text{ kPa}) = \mathbf{50 \ kPa}$$

$$P_{CO_2} = y_{CO_2} P = (0.15)(250 \text{ kPa}) = \mathbf{37.5 \ kPa}$$

14-20 The binary diffusion coefficients of CO_2 in air at various temperatures and pressures are to be determined.

Assumptions The mixture is sufficiently dilute so that the diffusion coefficient is independent of mixture composition.

Properties The binary diffusion coefficients of CO_2 in air at 1 atm pressure are given in Table 14-1 to be 0.74×10^{-5}, 2.63×10^{-5}, and 5.37×10^{-5} m^2/s at temperatures of 200 K, 400 K, and 600 K, respectively.

Analysis Noting that the binary diffusion coefficients of gases are inversely proportional to pressure, the diffusion coefficients at given pressures are determined from

$$D_{AB}(T,P) = D_{AB}(T,\ 1\text{ atm})/P$$

where P is in atm.

(a) At 200 K and 1 atm: D_{AB} (200 K, 1 atm) = $\mathbf{0.74\times10^{-5}}$ **m^2/s** (since P = 1 atm).

(b) At 400 K and 0.8 atm: D_{AB}(400 K, 0.8 atm)=D_{AB}(400 K, 1 atm)/0.8=(2.63×10^{-5})/0.8 = $\mathbf{3.29\times10^{-5}}$ **m^2/s**

(c) At 600 K and 3 atm: D_{AB}(600 K, 3 atm)=D_{AB}(600 K, 1 atm)/3=(5.37×10^{-5})/3 = $\mathbf{1.79\times10^{-5}}$ **m^2/s**

14-21 The binary diffusion coefficient of O_2 in N_2 at various temperature and pressures are to be determined.

Assumptions The mixture is sufficiently dilute so that the diffusion coefficient is independent of mixture composition.

Properties The binary diffusion coefficient of O_2 in N_2 at T_1 = 273 K and P_1 = 1 atm is given in Table 14-2 to be 1.8×10^{-5} m^2/s.

Analysis Noting that the binary diffusion coefficient of gases is proportional to 3/2 power of temperature and inversely proportional to pressure, the diffusion coefficients at other pressures and temperatures can be determined from

$$\frac{D_{\text{AB},1}}{D_{\text{AB},2}} = \frac{P_2}{P_1}\left(\frac{T_1}{T_2}\right)^{3/2} \rightarrow D_{\text{AB},2} = D_{\text{AB},1}\frac{P_1}{P_2}\left(\frac{T_2}{T_1}\right)^{3/2}$$

(a) At 200 K and 1 atm: $D_{\text{AB},2} = (1.8\times10^{-5}\ \text{m}^2/\text{s})\dfrac{1\,\text{atm}}{1\,\text{atm}}\left(\dfrac{200\,\text{K}}{273\text{K}}\right)^{3/2} = \mathbf{1.13\times10^{-5}\ m^2/s}$

(b) At 400 K and 0.8 atm: $D_{\text{AB},2} = (1.8\times10^{-5}\ \text{m}^2/\text{s})\dfrac{1\,\text{atm}}{0.8\,\text{atm}}\left(\dfrac{400\,\text{K}}{273\text{K}}\right)^{3/2} = \mathbf{4.0\times10^{-5}\ m^2/s}$

(c) At 600 K and 3 atm: $D_{\text{AB},2} = (1.8\times10^{-5}\ \text{m}^2/\text{s})\dfrac{1\,\text{atm}}{3\,\text{atm}}\left(\dfrac{600\,\text{K}}{273\text{K}}\right)^{3/2} = \mathbf{1.95\times10^{-5}\ m^2/s}$

14-22E The error involved in assuming the density of air to remain constant during a humidification process is to be determined.

Properties The density of moist air before and after the humidification process is determined from the psychrometric chart to be

$$\left.\begin{array}{l} T_1 = 80^\circ\text{F} \\ \phi_1 = 30\% \end{array}\right\} \rho_{air,1} = 0.0727\text{lbm/ft}^3 \quad \text{and} \quad \left.\begin{array}{l} T_1 = 80^\circ\text{F} \\ \phi_1 = 90\% \end{array}\right\} \rho_{air,2} = 0.07117\text{lbm/ft}^3$$

Analysis The error involved as a result of assuming constant air density is then determined to be

$$\%\text{Error} = \frac{\Delta\rho_{air}}{\rho_{air,1}} \times 100 = \frac{0.0727 - 0.0712 \text{ lbm/ft}^3}{0.0727 \text{ lbm/ft}^3} \times 100 = \mathbf{2.1\%}$$

which is acceptable for most engineering purposes.

Air
80°F
14.7 psia
RH_1=30%
RH_2=90%

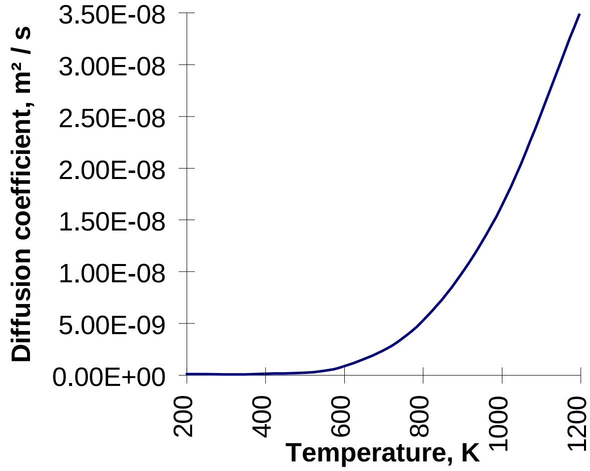
14-23 The diffusion coefficient of hydrogen in steel is given as a function of temperature. The diffusion coefficients from 200 K to 1200 K in 200 K increments are to be determined and plotted.

Properties The diffusion coefficient of hydrogen in steel between 200 K and 1200 K is given as

$$D_{AB} = 1.65 \times 10^{-6} \exp(-4630/T) \quad \text{m}^2/\text{s}$$

Analysis Using the relation above, the diffusion coefficients are calculated, and the results are tabulated and plotted below:

T (K)	D_{AB}, m²/s
200	1.457×10^{-16}
400	1.550×10^{-11}
600	7.348×10^{-10}
800	5.058×10^{-9}
1000	1.609×10^{-8}
1200	3.482×10^{-8}



14-24 "!PROBLEM 14-24"

"GIVEN"
"The diffusion coeffcient of hydrogen in steel as a function of temperature is given"

"ANALYSIS"
D_AB=1.65E-6*exp(-4630/T)

T [K]	D_{AB} [m^2/s]
200	1.457E-16
250	1.494E-14
300	3.272E-13
350	2.967E-12
400	1.551E-11
450	5.611E-11
500	1.570E-10
550	3.643E-10
600	7.348E-10
650	1.330E-09
700	2.213E-09
750	3.439E-09
800	5.058E-09
850	7.110E-09
900	9.622E-09
950	1.261E-08
1000	1.610E-08
1050	2.007E-08
1100	2.452E-08
1150	2.944E-08
1200	3.482E-08

Boundary Conditions

14-25C Three boundary conditions for mass transfer (on mass basis) that correspond to specified temperature, specified heat flux, and convection boundary conditions in heat transfer are expressed as follows:

1) $w(0) = w_0$ (specified concentration - corresponds to specified temperature)

2) $-\rho D_{AB} \left.\frac{dw_A}{dx}\right|_{x=0} = J_{A,0}$ (specified mass flux - corresponds to specified heat flux)

3) $j_{A,s} = -D_{AB} \left.\frac{\partial w_A}{\partial y}\right|_{x=0} = h_{mass}(w_{A,s} - w_{A,\infty})$ (mass convection - corresponds to heat convection)

14-26C An impermeable surface is a surface that does not allow any mass to pass through. Mathematically it is expressed (at $x = 0$) as

$$\left.\frac{dw_A}{dx}\right|_{x=0} = 0$$

An impermeable surface in mass transfer corresponds to an insulated surface in heat transfer.

14-27C Temperature is necessarily a *continuous* function, but concentration, in general, is not. Therefore, the mole fraction of water vapor in air will, in general, be different from the mole fraction of water in the lake (which is nearly 1).

14-28C When prescribing a boundary condition for mass transfer at a solid-gas interface, we need to specify the side of the surface (whether the solid or the gas side). This is because concentration, in general, is not a continuous function, and there may be large differences in concentrations on the gas and solid sides of the boundary. We did not do this in heat transfer because temperature is a continuous function.

14-29C The mole fraction of the water vapor at the surface of a lake when the temperature of the lake surface and the atmospheric pressure are specified can be determined from

$$y_{vapor} = \frac{P_{vapor}}{P} = \frac{P_{sat@T}}{P_{atm}}$$

where P_{vapor} is equal to the saturation pressure of water at the lake surface temperature.

14-30C Using solubility data of a solid in a specified liquid, the mass fraction w of the solid A in the liquid at the interface at a specified temperature can be determined from

$$w_A = \frac{m_{solid}}{m_{solid} + m_{liquid}}$$

where m_{solid} is the maximum amount of solid dissolved in the liquid of mass m_{liquid} at the specified temperature.

14-31C The molar concentration C_i of the gas species i in the solid at the interface $C_{i,\ solid\ side}(0)$ is proportional to the *partial pressure* of the species i in the gas $P_{i,\ gas\ side}(0)$ on the gas side of the interface, and is determined from

$$C_{\text{i, solid side}}(0) = \text{S} \times P_{\text{i, gas side}}(0) \qquad (\text{kmol/m}^3)$$

where S is the *solubility* of the gas in that solid at the specified temperature.

14-32C Using Henry's constant data for a gas dissolved in a liquid, the mole fraction of the gas dissolved in the liquid at the interface at a specified temperature can be determined from Henry's law expressed as

$$y_{\text{i, liquid side}}(0) = \frac{P_{\text{i, gas side}}(0)}{H}$$

where H is *Henry's constant* and $P_{\text{i, gas side}}(0)$ is the partial pressure of the gas i at the gas side of the interface. This relation is applicable for dilute solutions (gases that are weakly soluble in liquids).

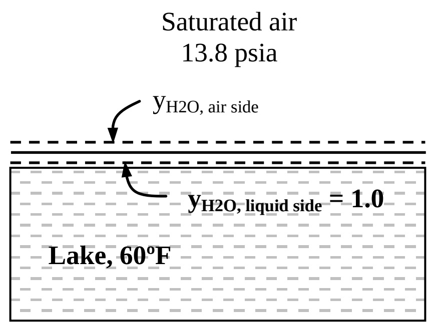
14-33C The permeability is a measure of the ability of a gas to penetrate a solid. The permeability of a gas in a solid, P**,** is related to the solubility of the gas by P = SD_{AB} where D_{AB} is the diffusivity of the gas in the solid.

14-34E The mole fraction of the water vapor at the surface of a lake and the mole fraction of water in the lake are to be determined and compared.

Assumptions **1** Both the air and water vapor are ideal gases. **2** Air is weakly soluble in water and thus Henry's law is applicable.

Properties The saturation pressure of water at 60°F is 0.2563 psia (Table A-9E). Henry's constant for air dissolved in water at 60ºF (289 K) is given in Table 14-6 to be H = 62,000 bar.

Analysis The air at the water surface will be saturated. Therefore, the partial pressure of water vapor in the air at the lake surface will simply be the saturation pressure of water at 15°C,



$$P_{\text{vapor}} = P_{\text{sat@60°F}} = 0.2563 \text{ psia}$$

Assuming both the air and vapor to be ideal gases, the mole fraction of water vapor in the air at the surface of the lake is determined from Eq. 14-11 to be

$$y_{\text{vapor}} = \frac{P_{\text{vapor}}}{P} = \frac{0.2563 \text{ psia}}{13.8 \text{ psia}} = \mathbf{0.0186 \text{ (or 1.86 percent)}}$$

The partial pressure of dry air just above the lake surface is

$$P_{\text{dry air}} = P - P_{\text{vapor}} = 13.8 - 0.2563 = 13.54 \text{ psia}$$

Then the mole fraction of air in the water becomes

$$y_{\text{dry air,liquid side}} = \frac{P_{\text{dry air,gasside}}}{H} = \frac{13.54 \text{ psia}(1 \text{ atm}/14.696 \text{ psia})}{62{,}000 \text{ bar}(1 \text{ atm}/1.01325 \text{ bar})} = 1.51\times10^{-5}$$

which is very small, as expected. Therefore, the mole fraction of water in the lake near the surface is

$$y_{\text{water,liquid side}} = 1 - y_{\text{dry air, liquid side}} = 1 - 1.51\times10^{-5} = \mathbf{0.9999}$$

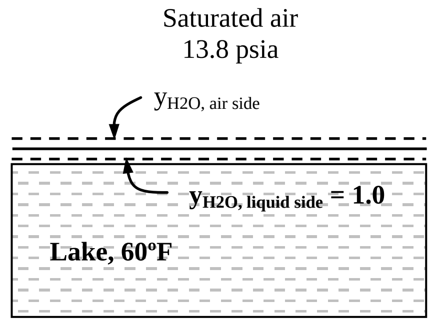
Discussion The concentration of air in water just below the air-water interface is 1.51 moles per 100,000 moles. The amount of air dissolved in water will decrease with increasing depth.

14-35 The mole fraction of the water vapor at the surface of a lake at a specified temperature is to be determined.

Assumptions **1** Both the air and water vapor are ideal gases. **2** Air at the lake surface is saturated.

Properties The saturation pressure of water at 15°C is 1.705 kPa (Table A-9).

Analysis The air at the water surface will be saturated. Therefore, the partial pressure of water vapor in the air at the lake surface will simply be the saturation pressure of water at 15°C,



$$P_{\text{vapor}} = P_{\text{sat@15°C}} = 1.705 \text{ kPa}$$

Assuming both the air and vapor to be ideal gases, the partial pressure and mole fraction of dry air in the air at the surface of the lake are determined to be

$$P_{\text{dry air}} = P - P_{\text{vapor}} = 100 - 1.705 = 98.295 \text{ kPa}$$

$$y_{\text{dry air}} = \frac{P_{\text{dry air}}}{P} = \frac{98.295 \text{ kPa}}{100 \text{ kPa}} = \mathbf{0.983} \quad \text{(or 98.3\%)}$$

Therefore, the mole fraction of dry air is 98.3 percent just above the air-water interface.

14-36 "!PROBLEM 14-36"

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"GIVEN"
"T=15 [C], parameter to be varied"
P_atm=100 "[kPa]"

"PROPERTIES"
Fluid$='steam_NBS'
P_sat=Pressure(Fluid$, T=T, x=1)

"ANALYSIS"
P_vapor=P_sat
P_dryair=P_atm-P_vapor
y_dryair=P_dryair/P_atm
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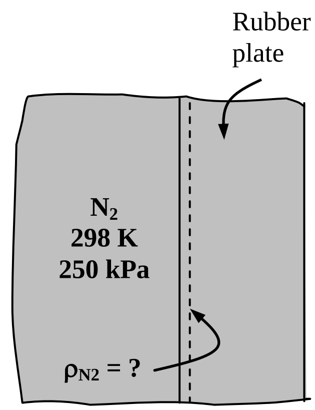
T [C]	$y_{dry\ air}$
5	0.9913
6	0.9906
7	0.99
8	0.9893
9	0.9885
10	0.9877
11	0.9869
12	0.986
13	0.985
14	0.984
15	0.9829
16	0.9818
17	0.9806
18	0.9794
19	0.978
20	0.9766
21	0.9751
22	0.9736
23	0.9719
24	0.9701
25	0.9683

14-37 A rubber plate is exposed to nitrogen. The molar and mass density of nitrogen in the rubber at the interface is to be determined.

Assumptions Rubber and nitrogen are in thermodynamic equilibrium at the interface.

Properties The molar mass of nitrogen is M = 28.0 kg/kmol (Table A-1). The solubility of nitrogen in rubber at 298 K is 0.00156 kmol/m^3·bar (Table 14-7).



Analysis Noting that 250 kPa = 2.5 bar, the molar density of nitrogen in the rubber at the interface is determined from Eq. 14-20 to be

$$C_{N_2,\text{solid side}}(0) = \mathcal{S} \times P_{N_2,\text{gas side}}$$
$$= (0.00156\,\text{kmol/m}^3.\text{bar})(2.5\,\text{bar})$$
$$= \mathbf{0.0039 kmol/m^3}$$

It corresponds to a mass density of

$$\rho_{N_2,\text{ solid side}}(0) = C_{N_2,\text{ solid side}}(0) M_{N_2}$$
$$= (0.0039\text{ kmol / m}^3)(28\text{ kmol / kg})$$
$$= \mathbf{0.1092\ kg / m^3}$$

That is, there will be 0.0039 kmol (or 0.1092 kg) of N_2 gas in each m^3 volume of rubber adjacent to the interface.

14-38 A rubber wall separates O_2 and N_2 gases. The molar concentrations of O_2 and N_2 in the wall are to be determined.

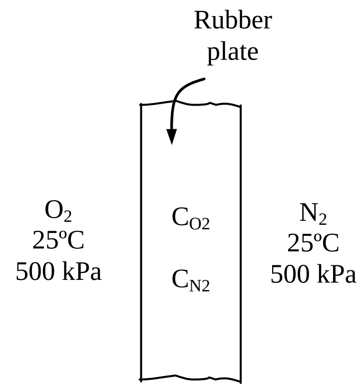
Assumptions The O_2 and N_2 gases are in phase equilibrium with the rubber wall.

Properties The molar mass of oxygen and nitrogen are 32.0 and 28.0 kg/kmol, respectively (Table A-1). The solubility of oxygen and nitrogen in rubber at 298 K are 0.00312 and 0.00156kmol/m^3·bar, respectively (Table 14-7).

Analysis Noting that 500 kPa = 5 bar, the molar densities of oxygen and nitrogen in the rubber wall are determined from Eq. 14-20 to be

$$C_{O_2,\text{solid side}}(0) = S \times P_{O_2,\text{gas side}} = (0.00312\,\text{kmol/m}^3.\text{bar})(5\text{ bar}) = \mathbf{0.0156\,kmol/m^3}$$

$$C_{N_2,\text{solid side}}(0) = S \times P_{N_2,\text{gas side}} = (0.00156\,\text{kmol/m}^3.\text{bar})(5\text{ bar}) = \mathbf{0.0078\,kmol/m^3}$$



That is, there will be 0.0156 kmol of 039 kmol of O_2 and 0.0078 kmol of N_2 gas in each m^3 volume of the rubber wall.

14-39 A glass of water is left in a room. The mole fraction of the water vapor in the air and the mole fraction of air in the water are to be determined when the water and the air are in thermal and phase equilibrium.

Assumptions **1** Both the air and water vapor are ideal gases. **2** Air is saturated since the humidity is 100 percent. **3** Air is weakly soluble in water and thus Henry's law is applicable.

Properties The saturation pressure of water at 20°C is 2.339 kPa (Table A-9). Henry's constant for air dissolved in water at 20ºC (293 K) is given in Table 14-6 to be H = 65,600 bar. Molar masses of dry air and water are 29 and 18 kg/kmol, respectively (Table A-1).

Analysis (*a*) Noting that air is saturated, the partial pressure of water vapor in the air will simply be the saturation pressure of water at 20°C,

$$P_{\text{vapor}} = P_{sat@20^\circ C} = 2.339\text{ kPa}$$

Assuming both the air and vapor to be ideal gases, the mole fraction of water vapor in the air is determined to be

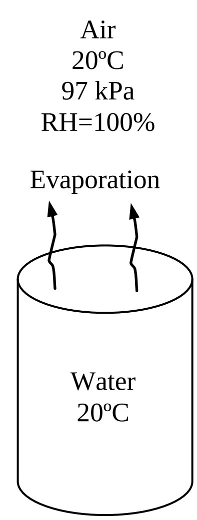
$$y_{\text{vapor}} = \frac{P_{\text{vapor}}}{P} = \frac{2.339\text{ kPa}}{97\text{ kPa}} = \mathbf{0.0241}$$

(*b*) Noting that the total pressure is 97 kPa, the partial pressure of dry air is

$$P_{dry\ air} = P - P_{vapor} = 97 - 2.339 = 94.7\,\text{kPa} = 0.94\text{ bar}$$

From Henry's law, the mole fraction of air in the water is determined to be

$$y_{\text{dry air,liquid side}} = \frac{P_{\text{dry air,gas side}}}{H} = \frac{0.947\text{ bar}}{65{,}600\,\text{bar}} = \mathbf{1.44 \times 10^{-5}}$$



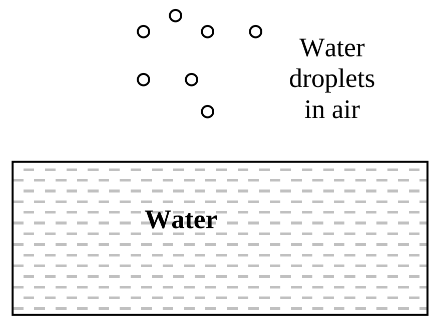
Discussion The amount of air dissolved in water is very small, as expected.

14-40E Water is sprayed into air, and the falling water droplets are collected in a container. The mass and mole fractions of air dissolved in the water are to be determined.

Assumptions **1** Both the air and water vapor are ideal gases. **2** Air is saturated since water is constantly sprayed into it. **3** Air is weakly soluble in water and thus Henry's law is applicable.

Properties The saturation pressure of water at 80°F is 0.5073 psia (Table A-9E). Henry's constant for air dissolved in water at 80ºF (300 K) is given in Table 14-6 to be H = 74,000 bar. Molar masses of dry air and water are 29 and 18 lbm / lbmol, respectively (Table A-1).

Analysis Noting that air is saturated, the partial pressure of water vapor in the air will simply be the saturation pressure of water at 80°F,



$$P_{\text{vapor}} = P_{\text{sat@80°F}} = 0.5073 \text{ psia}$$

Then the partial pressure of dry air becomes

$$P_{\text{dry air}} = P - P_{\text{vapor}} = 14.3 - 0.5073 = 13.79 \text{ psia}$$

From Henry's law, the mole fraction of air in the water is determined to be

$$y_{\text{dry air,liquid side}} = \frac{P_{\text{dry air,gasside}}}{H} = \frac{13.79 \text{ psia}(1 \text{ atm} / 14.696 \text{ psia})}{74{,}000 \text{ bar}(1 \text{ atm} / 1.01325 \text{ bar})} = \mathbf{1.29 \times 10^{-5}}$$

which is very small, as expected. The mass and mole fractions of a mixture are related to each other by

$$w_i = \frac{m_i}{m_m} = \frac{N_i M_i}{N_m M_m} = y_i \frac{M_i}{M_m}$$

where the apparent molar mass of the liquid water - air mixture is

$$M_m = \sum y_i M_i = y_{\text{liquid water}} M_{\text{water}} + y_{\text{dry air}} M_{\text{dry air}}$$
$$\cong 1 \times 29.0 + 0 \times 18.0 \cong 29.0 \text{ kg / kmol}$$

Then the mass fraction of dissolved air in liquid water becomes

$$w_{\text{dryair, liquidside}} = y_{\text{dryair, liquidside}}(0) \frac{M_{\text{dryair}}}{M_m} = 1.29 \times 10^{-5} \frac{29}{29} = \mathbf{1.29 \times 10^{-5}}$$

Discussion The mass and mole fractions of dissolved air in this case are identical because of the very small amount of air in water.

14-41 A carbonated drink in a bottle is considered. Assuming the gas space above the liquid consists of a saturated mixture of CO_2 and water vapor and treating the drink as a water, determine the mole fraction of the water vapor in the CO_2 gas and the mass of dissolved CO_2 in a 200 ml drink are to be determined when the water and the CO_2 gas are in thermal and phase equilibrium.

Assumptions **1** The liquid drink can be treated as water. **2** Both the CO_2 and the water vapor are ideal gases. **3** The CO_2 gas and water vapor in the bottle from a saturated mixture. **4** The CO_2 is weakly soluble in water and thus Henry's law is applicable.

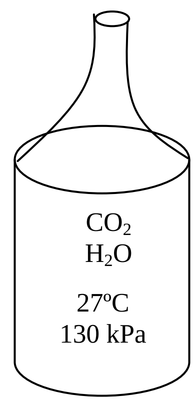
Properties The saturation pressure of water at 27°C is 3.60 kPa (Table A-9). Henry's constant for CO_2 dissolved in water at 27ºC (300 K) is given in Table 14-6 to be H = 1710 bar. Molar masses of CO_2 and water are 44 and 18 kg/kmol, respectively (Table A-1).

Analysis (*a*) Noting that the CO_2 gas in the bottle is saturated, the partial pressure of water vapor in the air will simply be the saturation pressure of water at 27°C,

$$P_{\text{vapor}} = P_{sat@27°C} = 3.60 \text{ kPa}$$

Assuming both CO_2 and vapor to be ideal gases, the mole fraction of water vapor in the CO_2 gas becomes

$$y_{\text{vapor}} = \frac{P_{\text{vapor}}}{P} = \frac{3.60 \text{ kPa}}{130 \text{ kPa}} = \mathbf{0.0277}$$



(*b*) Noting that the total pressure is 130 kPa, the partial pressure of CO_2 is

$$P_{\text{CO}_2\text{ gas}} = P - P_{vapor} = 130 - 3.60 = 126.4 \text{ kPa} = 1.264 \text{ bar}$$

From Henry's law, the mole fraction of CO_2 in the drink is determined to be

$$y_{\text{CO}_2\text{, liquid side}} = \frac{P_{\text{CO}_2\text{, gas side}}}{H} = \frac{1.264 \text{ bar}}{1710 \text{ bar}} = \mathbf{7.39 \times 10^{-4}}$$

Then the mole fraction of water in the drink becomes

$$y_{\text{water, liquid side}} = 1 - y_{\text{CO}_2\text{, liquid side}} = 1 - 7.39 \times 10^{-4} = 0.9993$$

The mass and mole fractions of a mixture are related to each other by

$$w_i = \frac{m_i}{m_m} = \frac{N_i M_i}{N_m M_m} = y_i \frac{M_i}{M_m}$$

where the apparent molar mass of the drink (liquid water - CO_2 mixture) is

$$M_m = \sum y_i M_i = y_{\text{liquid water}} M_{\text{water}} + y_{\text{CO}_2} M_{\text{CO}_2} = 0.9993 \times 18.0 + (7.39 \times 10^{-4}) \times 18.0 = 18.02 \text{ kg/kmol}$$

Then the mass fraction of dissolved CO_2 gas in liquid water becomes

$$w_{\text{CO}_2\text{, liquid side}} = y_{\text{CO}_2\text{, liquid side}}(0) \frac{M_{\text{CO}_2}}{M_m} = 7.39 \times 10^{-4} \frac{44}{18.02} = 0.00180$$

Therefore, the mass of dissolved CO_2 in a 200 ml ≈ 200 g drink is

$$m_{\text{CO}_2} = w_{\text{CO}_2} m_m = 0.00180(200 \text{ g}) = \mathbf{0.360 \text{ g}}$$