(1). A steady-state Arnold cell is used to determine the diffusivity of toluene (species A) in air (species B) at 298 K and 1 atm. If the diffusivity is $D_{AB} = 0.0844 \text{ cm}^2/\text{s} = 8.44 \times 10^{-6} \text{ m}^2/\text{s}$, and the cell has a 0.8 cm$^2$ cross-sectional area and a constant diffusion path length of 10 cm, how much toluene in units of cm$^3$ per hour must be supplied to the cell to maintain a constant liquid level? At 298K, the vapor pressure of toluene is 28.4 mmHg and its specific gravity is 0.866.

Comments:
Note that concentration of toluene in the air blowing past the top of the Arnold cell is effectively zero as it is extremely dilute. The molar mass of toluene is 92.13 g/mol.

(2). A spherical ball of solid, nonporous naphthalene, a “moth ball,” is suspended in still air. The naphthalene ball slowly sublimes, releasing the naphthalene into the surrounding air by a diffusion limited process. Estimate the time required to reduce the diameter from 2 cm to 0.5 cm when the surrounding air is at 347 K and 1.013 $\times$ $10^5$ Pa. Naphthalene has a molecular weight of 128 g/mole, a solid density of 1.145 g/cm$^3$, a diffusion coefficient in air of $8.19 \times 10^{-6}$ m$^2$/s, and exerts a vapor pressure of 5 torr (670 Pa) at 347 K. While this problem is not strictly steady state, for purposes of the approximate calculation you may treat it as steady state.

(3). In the manufacture of semiconducting thin films, a thin film of solid arsenic is laid down onto the surface of a silicon wafer by the chemical vapor deposition of arsenic, AsH$_3$
\[2\text{AsH}_3(g) \rightarrow 2\text{As(s)} + 3\text{H}_2(g)\]

The arsenic atoms then diffuse into the solid silicon to dope the wafer. What is the flux of arsenic atoms into the silicon wafer after one hour, in units of atoms/cm\(^2\)•s? What is the arsenic concentration 2 microns into the silicon wafer after one hour, in units of atoms/cm\(^3\)? The initial concentration of residual arsenic in the silicon wafer is \(10^{12}\) atoms/cm\(^3\). The process temperature is 1050°C. The average diffusivity of arsenic in silicon is \(5 \times 10^{-13}\) cm\(^2\)/s at this temperature, and its maximum solubility in silicon is \(2 \times 10^{21}\) atoms/cm\(^3\).

**COMMENTS:**
The Si wafer can be considered to be semi-infinite. Also, tabulated values of the error function can be found at [https://www.miniwebtool.com/error-function-calculator/](https://www.miniwebtool.com/error-function-calculator/).

**A.** A 750 Watt immersion heater in the form of a cylinder with a 0.75 inch diameter and 6 inches in length is placed in 20°C stagnant water. The cylinder is oriented with its axis horizontal. Heating of the water produces free (natural) convection of water around the cylinder. This free convection removes heat from the cylinder's surface at a rate that can be calculated with the help of the following correlation established from experimental data:

\[
\text{Nu} = \left\{ 0.60 + \frac{0.387\text{Ra}^{1/6}}{1 + (0.559/\text{Pr})^{9/16}} \right\}^{2/27}
\]

This correlation was derived for cylinders with a high aspect ratio (as in the present problem), immersed in a fluid reservoir and oriented horizontal (that is, perpendicular to the gravitational field). \(\text{Nu}\) is the Nusselt number, \(\text{Pr}\) is the Prandtl number, and \(\text{Ra}\) is the Rayleigh number. For this situation, these dimensionless groups are defined as follows:

\[
\text{Nu} = \frac{hD}{\kappa}
\]
\[
\text{Pr} = \frac{\mu\hat{c}_p}{\kappa}
\]
\[
\text{Ra} = D^3 \rho_0 \beta \Delta T / (\mu \alpha)
\]

\(D\) is the cylinder radius, \(g\) is the gravitational constant, \(\rho_0\) is the density of the fluid at the bulk temperature, \(\beta\) is the coefficient of thermal expansion of the fluid, \(\Delta T\) is the temperature difference between surface of the cylinder and bulk fluid, \(\mu\) is the fluid viscosity, \(\alpha\) is the thermal diffusivity of the fluid, \(\kappa\) is the thermal conductivity of the fluid, and \(h\) is the heat transfer coefficient describing heat transfer from the cylinder to the surrounding fluid due to free convection. \(\text{Ra}\) can be shown to equal the product of the Grashof and Prandtl numbers, \(\text{Ra} = \text{Gr} \times \text{Pr}\). The product \(\rho_0 \beta \Delta T\) equals the difference in density between fluid at the cylinder surface and in the bulk. In the above expressions, the properties of the fluid (other than \(\rho_0\)) are evaluated at the surface temperature of the cylinder.
Calculate the surface temperature of the cylinder, given that steady state applies (Note: a trial and error solution is required). Properties of water as a function of temperature can be found at http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html.

(5). A cooking oven has a top surface temperature of 45 C when exposed to still air. At this condition the inside oven temperature and room air temperature are 180 C and 20 C, respectively, and heat is transferred from the top surface at 40 W. To reduce the surface temperature, as required by safety regulations, room air is blown across the top with a velocity of 20 m/s, which is measured to reduce the surface temperature to 24 C. What will be the rate of heat transfer from the top surface under this new operating condition?

COMMENTS:
When the room air is still (initial situation), the heat transfer from the oven top to the air is by natural convection only. Under this situation we can take

$$Nu_L = 0.15 \, Ra^{1/3} \quad \text{(works for } 10^7 < Ra < 10^{11})$$

Assume the shape of the oven top is square, with a length $L$ on each side (you'll need to figure out what $L$ is from the given information – note that the total rate of heat transfer is given in Watts, rather than a heat flux).

For the forced convection case when air is blown across the top of the oven, there are several options of correlations. Two are reproduced below (the laminar flow correlation follows from boundary layer theory)

$$Nu_L = 0.664 \, Re_L^{1/2} \, Pr^{1/3} \quad \text{(works for laminar flow, } Re_L < 5 \times 10^5)$$

$$Nu_L = (0.037 \, Re_L^{4/5} - 871)Pr^{1/3} \quad \text{(works for transition flow, } 5 \times 10^5 < Re_L < 1 \times 10^7)$$

You can assume that the heat transfer from the top of the oven is dominated by forced convection (i.e. the forced convection heat transfer is much larger than any residual natural convection transfer).

In these correlations the properties of air are to be evaluated at the film temperature $T_f$, which is the average of the surface and bulk temperatures. Properties of air are at http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html.

Note that the internal oven temperature of 180 C is not needed in this problem. The subscript $L$ indicates to use $L$ as the characteristic dimension of the problem.

(6). Trichloroethane, Cl$_3$CCH$_3$ (TCA), is used to chlorinate films of SiO$_2$ grown by thermal oxidation. A semiconductor fabrication process has been proposed involving the evaporating of the TCA into a flowing inert gas stream. A pan will contain the liquid TCA at a starting depth of 0.01 m and a length of 4 m in the direction that inert gas will flow at 6 m/s. The pan is quite wide. The liquid TCA will be maintained at a temperature of 293K and the system’s pressure will be 1.013 $\times$ 10$^5$ Pa. Under these conditions, the vapor pressure of TCA is 1.33 $\times$ 10$^4$ Pa, the kinematic viscosity of the inert gas is $\nu = \mu/\rho = 1.5 \times 10^{-5}$ m$^2$/s, and the diffusivity of TCA may
be assumed to be $1.0 \times 10^{-5}$ m$^2$/s. If the density of the liquid TCA is assumed to be 1 g/cm$^3$ and the transition from laminar to turbulent occurs at $Re_t = 2 \times 10^5$, determine the time that will be required to evaporate the TCA. The molar mass of TCA is 133 g/mol.

**COMMENTS:**
Above it states that the transition from laminar to turbulent flow of the gas over the pan occurs at $Re_t = 2 \times 10^5$. For flows over a flat surface like the pan, the flow remains laminar for short distances but as the length of the surface (here pan) increases the perturbation to the flow builds and a transition from laminar to turbulent flow takes place. This is quantified by the Reynolds number, which is defined as

$$Re_x = \rho V x / \mu$$

where $x$ is the distance traveled along the surface and $V$ is the velocity of the flow far from the surface, where it remains unperturbed. Thus, $Re_x$ increases with distance from the leading edge of the pan. This means that mass transfer over the initial section of the pan, for which $Re_x < Re_t$, will follow the correlation for laminar flow, while that from the remaining area of the pan where $Re_x > Re_t$ will obey the correlation for turbulent flow. The applicable correlation for such a combined situation of laminar and turbulent flows can be obtained by averaging over the full length of the pan, leading to

$$\frac{1}{k_c} = \frac{0.664D_{AB}S_c^{1/3} Re_t^{1/2} + 0.0365D_{AB}S_c^{1/3} (Re_L^{4/5} - Re_t^{4/5})}{L}$$

The above equation provides an expression for an averaged mass transfer coefficient for a plate of total length $L$ over which part of the flow is laminar (corresponding to first term in the numerator) and part turbulent (the second term in the numerator).

(7). Determine the value of Henry’s law constant, in Pa/mole fraction of ammonia (as $x_{NH3} \rightarrow 0$) for ammonia (NH$_3$) in water. The following equilibrium data at 298 K were reported in the Chemical Engineering Handbook:

<table>
<thead>
<tr>
<th>partial pressure NH$_3$, mmHg</th>
<th>3.4</th>
<th>7.4</th>
<th>9.1</th>
<th>12.0</th>
<th>15.3</th>
<th>19.4</th>
<th>23.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt NH$_3$/100 wt of water</td>
<td>0.5</td>
<td>1.0</td>
<td>1.2</td>
<td>1.6</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Take the molar mass of ammonia as 17.03 g/mol.

(8). An absorption tower, operating at 293 K and $1.013 \times 10^5$ Pa, was used to absorb SO$_2$ from an air mixture into water. At one point in the equipment, the partial pressure of the SO$_2$ on the gas stream was $4 \times 10^3$ Pa and the concentration of the contacting liquid stream was 0.55 kgmole/m$^3$. The individual film mass-transfer coefficients at 293 K and $1.013 \times 10^5$ Pa were
\[ k_G = 3.95 \times 10^{-9} \text{ kgmole/m}^2\text{s Pa} \]

and

\[ k_L = 1.1 \times 10^{-4} \text{ kgmole/m}^2\text{s (kgmole/m}^3) \]

Equilibrium data at 293 K are as follows:

<table>
<thead>
<tr>
<th>Partial pressure SO₂, Pa</th>
<th>67</th>
<th>426</th>
<th>1132</th>
<th>3466</th>
<th>7864</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration in kgmole/m³ soln</td>
<td>0.306</td>
<td>1.458</td>
<td>2.780</td>
<td>6.208</td>
<td>10.896</td>
</tr>
</tbody>
</table>

COMMENTS: A kmol is a number of particles equal to 1000 times Avogadro's number (i.e. 1 kmol = 6.02 × 10²⁶ particles). The place to start for part (a) is to equate the molar fluxes on the gas and liquid sides of the interface (assuming no accumulation at the interface) and to make use of the equilibrium data provided. You may wish to fit the equilibrium data to a polynomial for ease of interpolation, but this is not necessary (i.e. manual interpolation between the given values is fine).

(a) Evaluate the interfacial concentration, \( c_{AI} \), and \( p_{AI} \).

(b) Fill in the values for the following table, giving the various coefficients and the associated driving force.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Driving Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_G )</td>
<td>( p_{AG} - p_{AI} )</td>
</tr>
<tr>
<td>( k_L )</td>
<td>( c_{AI} - c_{AL} )</td>
</tr>
<tr>
<td>( K_G )</td>
<td>( p_{AG} - p_{A*} )</td>
</tr>
<tr>
<td>( K_L )</td>
<td>( c_{A*} - c_{AL} )</td>
</tr>
</tbody>
</table>

(c) What percentage of the overall mass-transfer resistance is in the gas film?

(9). The outside walls of a house are constructed of a 4-in. layer of brick, \( \frac{1}{2} \) in. of celotex, an air space \( \frac{5}{8} \) in. thick, and \( \frac{1}{4} \) in. of wood paneling. If the outside surface of the brick is at 30°F and the inner surface of the paneling at 75°F, what is the heat flux if the air space is assumed to transfer heat by conduction only? Below are the needed thermal conductivities:

\[ k_{\text{brick}} = 0.38 \text{ Btu/hr ft oF} \]

\[ k_{\text{celotex}} = 0.028 \text{ Btu/hr ft oF} \]

\[ k_{\text{air}} = 0.015 \text{ Btu/hr ft oF} \]

\[ k_{\text{wood}} = 0.12 \text{ Btu/hr ft oF} \]