## Acid Rain

Acid rain is a growing worldwide environmental problem. Naturally, rainwater should have a pH of not less than 5.5, but in the northeastern United States, for example, the average pH of rainwater is about 4.5. The increased acidity of the rain kills plants and animals in lakes and streams, causes increased weathering and decomposition of limestone in statues and on buildings (posing a major threat to Greek antiquities), and creates problems with the production of fruit and vegetable crops. The major chemical involved is sulfur dioxide, $\text{SO}_2$, which combines with rainwater to form sulfuric acid. Atmospheric $\text{SO}_2$ has many sources, with volcanoes being the primary natural contributor. However, the burning of fossil fuel as the result of human industrialization has led to a significant increase in atmospheric $\text{SO}_2$ levels. The number of moles $n$ of $\text{SO}_2$ released from a coal-burning power plant can be determined from the density $\rho$, volume $V$, and the molar mass $M$ of $\text{SO}_2$ gas given off by the power plant.

### Part A

If a given power plant released $\text{SO}_2$ gas with a volume $V$ of 1200 $\text{m}^3$ at a density $\rho$ of 2.86 $\text{kg/m}^3$ at standard pressure and temperature, how many moles $n$ of $\text{SO}_2$ are released?

*Hint A.1 How to approach the problem*

To find the number of moles of $\text{SO}_2$ you should find the mass of the gas and then use the molar mass of $\text{SO}_2$ to find the number of moles of gas produced.

*Hint A.2 Find the mass of sulfur dioxide*

Given that the volume of $\text{SO}_2$ is 1200 $\text{m}^3$ and the density of the gas is 2.86 $\text{kg/m}^3$, what is the mass $m$ of $\text{SO}_2$ produced?

*Hint A.2.1 Determine the equation for mass*

Express your answer in kilograms to three significant figures.

**ANSWER:**

$$m = 3430 \text{ kg}$$

*Correct*

*Hint not displayed*

*Hint A.3 Find the molar mass of sulfur dioxide*

Once you know the total mass of $\text{SO}_2$ released, you must convert mass to moles. To do this, you need the molar mass $m_{\text{mol}}$ of the compound in grams per mole. The molar mass of a compound is numerically equal to the molecular mass of the compound in atomic mass units.

What is the molar mass $m_{\text{mol}}$ of $\text{SO}_2$?

*Hint A.3.1 Atomic weights of sulfur and oxygen*

The atomic weight of sulfur is 32.07 $\text{u}$ and the atomic weight of oxygen is 16.00 $\text{u}$.

Express your answer in grams per mole to four significant figures.

**ANSWER:**

$$m_{\text{mol}} = 64.08 \text{ g/mol}$$

*Answer Requested*

*Hint A.4 Convert to consistent units of mass*

Once the mass $m$ of $\text{SO}_2$ is known in kilograms and the molecular mass is known in grams per mole, you need to be able to mathematically cancel out the masses to obtain units of moles. To cancel the masses, they must be in the same units. The simplest conversion is from kilograms to grams.

What is the mass of $\text{SO}_2$ in grams?

*Hint A.5 Find the conversion from grams to moles*

Once the mass of $\text{SO}_2$ is known in grams and the molar mass is known in grams per mole, what mathematical operation should you use to cancel mass to get units of moles?

**ANSWER:**

$$n = 3.43\times10^8 \text{ mol}$$

*Correct*

Express your answer in moles to three significant figures.

**ANSWER:**

$$n = 5.36\times10^8 \text{ mol}$$

*Correct*

Chemistry and physics are highly related. Many processes in chemistry are also relevant to our understanding of physics. Both sciences strive to achieve mathematical descriptions of processes. By paying close attention to the units involved in the problem, and the algebra needed to convert one set of units into another, the maze of mathematics can be negotiated with fewer wrong turns. This problem exemplifies how to perform unit conversion.
**Gas in a Tank**

A tank is filled with an ideal gas at 400 K and pressure of 1.00 atm.

**Part A**

The tank is heated until the pressure of the gas in the tank doubles. What is the temperature of the gas?

**Hint A.1 How to approach the problem**

Since the gas is confined in the tank, the amount of gas and its volume don't change. Thus, you can apply the ideal-gas equation to the initial state, when \( T_1 = 400 \text{ K} \) and \( p_1 = 1.00 \text{ atm} \), and the final state when the pressure is twice the initial value, and consider the term \( nR/V \) as a constant.

**Hint A.2 Ideal-gas equation**

For an ideal gas the product of pressure \( p \) and volume \( V \) is proportional to the product of the number of moles \( n \) of the gas and the absolute temperature \( T \):

\[ pV = nRT \]

where \( R \) is the ideal-gas constant.

**Hint A.3 Find a relation between pressure and temperature**

Considering that the number of moles and volume of the gas are constant, which of the following expressions is correct? Let \( p_1 \) and \( T_1 \) be the initial pressure and temperature, and \( p_2 \) and \( T_2 \) the final pressure and temperature, respectively.

**ANSWER:**

- \( p_1 T_1 = p_2 T_2 \)
- \( p_2 = p_1 T_2 / T_1 \)
- \( p_1 = T_2 / T_1 \)
- \( p_2 T_2 = T_1 T_1 \)

**Correct**

Note that the final pressure is twice the initial value. Now you can solve for the final temperature.

**ANSWER:**

- 200 K
- 400 K
- 600 K
- 800 K

**Correct**

**Part B**

Having been heated to 800 K, at some point the tank starts to leak. By the time the leak is repaired, the tank is only half full, and the pressure of the remaining gas is again 1.00 atm. What is the temperature of the gas?

**Hint B.1 How to approach the problem**

Since the remaining gas is still confined in the tank, the volume hasn't changed. However, now the amount of gas is different. There is only half the number of moles left in the tank. Thus, you can apply the ideal-gas equation to the initial state, when \( T_1 = 800 \text{ K} \) and \( p_1 = 1.00 \text{ atm} \), and consider the term \( nR/V \) as a constant.

**Hint B.2 Find an expression for pressure and temperature**

Considering that the volume is constant and the final number of moles in the tank is half the original amount, which of the following expressions is correct? Let \( p_2 \) and \( T_2 \) be the initial pressure and temperature, and \( p_2 \) and \( T_2 \) the final pressure and temperature, respectively.

**ANSWER:**

- \( 2p_2 = p_1 T_2 \)
- \( p_2 = T_1 \)
- \( p_2 = T_2 / T_1 \)
- \( p_2 T_2 = p_1 T_1 \)

**Correct**

**The Oxygen Room**

A room with dimensions 7.00 m \( \times \) 8.00 m \( \times \) 2.50 m is to be filled with pure oxygen at 22.0°C and 1.00 atm. The molar mass of oxygen is 32.0 g/mol.

**Part A**
How many moles \( n_{\text{O}_2} \) of oxygen are required to fill the room?

**Hint A.1 How to approach the problem**
Use the ideal gas equation to calculate the number of moles of oxygen in the room. Be careful about the units when doing the calculations.

**Hint A.2 Using the correct units**
No matter which definition for the gas constant \( R \) is used, the temperature must be expressed in kelvins. Also, be sure to convert either the volume from cubic meters to liters or the pressure from atmospheres to pascals, but not both, to use one of the standard forms of the gas constant,

\[
R = 8.314 \text{ J/(mol \cdot K)} = 0.08206 \text{ liters \cdot atm/(mol \cdot K)}
\]

Express your answer using three significant figures.

**ANSWER:** \( n_{\text{O}_2} = 5780 \text{ mol} \) Correct

You could have converted the pressure to \( 1.013 \times 10^5 \text{ Pa} \), or used \( R = 8.314 \text{ J/(mol \cdot K)} \) or you could have converted the volume to \( 1.40 \times 10^4 \text{ liters} \) and used \( R = 0.08206 \text{ (liters \cdot atm)/(mol \cdot K)} \). When solving these problems, use whichever conversions (and the appropriate value for the gas constant) are easiest. However, no matter which method you use, always be sure to convert the temperature from degrees Celsius to kelvins.

**Part B**
What is the mass \( m_{\text{O}_2} \) of this oxygen?

Express your answer in kilograms to three significant figures.

**ANSWER:** \( m_{\text{O}_2} = 185 \text{ kg} \) Correct

---

**Ideal Gas Law and Internal Energy Pressure vs. Volume Graph Ranking Task**
Six thermodynamic states of the same monatomic ideal gas sample are represented in the figure.

**Part A**
Rank these states on the basis of the temperature of the gas sample in each state.

**Hint A.1 The ideal gas law**
An ideal gas sample of pressure \( P \), volume \( V \), temperature \( T \), and number of molecules \( N \) must obey the relationship

\[
pV = Nk_B T
\]

where \( k_B \) is Boltzmann's constant.

**Hint A.2 Determining temperature**
Since the same gas sample is involved in each state, the number of particles in the gas does not change. Therefore,

\[
pV = Nk_B T
\]

implies \( T \propto pV \) (\( T \) is directly proportional to the product \( pV \)). Conceptually, this should make sense. To maintain a high pressure in a large volume requires very rapidly moving (very hot) particles.

Rank from largest to smallest. To rank items as equivalent, overlap them.

**ANSWER:**

---

**Part B**
Rank the states on the basis of the average kinetic energy of the atoms in the gas sample at each state.

**Hint B.1 Definition of average kinetic energy**
Each particle in the gas sample has a different velocity and hence a different kinetic energy. The average kinetic energy of the particles in the gas \( K_{\text{avg}} \), however, can be easily determined and is directly proportional to the temperature of the gas \( T \):

\[
K_{\text{avg}} = \frac{3}{2} k_B T
\]
where $k_B$ is Boltzmann's constant. By this definition, temperature is a macroscopic way of measuring the microscopic average kinetic energy of gas particles.

Rank from largest to smallest. To rank items as equivalent, overlap them.

**ANSWER:**

Temperature is a macroscopic quantity proportional to the average kinetic energy of the atoms in the gas.

**Part C**

Rank the states on the basis of the internal energy of the gas sample at each state.

**Hint C.1 Definition of internal energy**

The internal energy of a gas $U$ is the sum of the kinetic and potential energies of all of its constituents. In the standard ideal gas model, we assume that the gas particles do not have any potential energy, so the internal energy is just the sum of all of the individual kinetic energies. Thus, knowing the relationship for the average kinetic energy $K_{\text{avg}}$ allows us to write a relationship for the internal energy of an ideal monatomic gas of $N$ particles as

$$U = N(K_{\text{avg}})$$

Therefore,

$$U = \frac{3}{2}Nk_B T,$$

where $T$ is the temperature of the gas and $k_B$ is Boltzmann's constant. Thus, the temperature, average kinetic energy, and total internal energy of an ideal gas are all directly proportional to one another.

Rank from largest to smallest. To rank items as equivalent, overlap them.

**ANSWER:**

Internal energy is a measure of the total energy contained in the gas. The total energy is the average energy per atom multiplied by the number of atoms. Since temperature is proportional to the average energy per atom, it is also proportional to the total energy in the gas.

**Compression of a Jaguar XK8 Cylinder**

A Jaguar XK8 convertible has an eight-cylinder engine. At the beginning of its compression stroke, one of the cylinders contains 499 cm$^3$ of air at atmospheric pressure ($1.01 \times 10^5$ Pa) and a temperature of 27.0°C. At the end of the stroke, the air has been compressed to a volume of 46.2 cm$^3$ and the gauge pressure has increased to $2.72 \times 10^5$ Pa.

**Part A**

Compute the final temperature $T_f$.

**Hint A.1 How to approach the problem**

Use the ideal gas law to relate the initial pressure, temperature, and volume to their final values. Calculate the final temperature given the initial and final values in the introduction. Also, be very careful about the units in your calculations.

**Hint A.2 Mass of air in the cylinder**

Because the air in the cylinder is trapped and cannot enter or leave, the mass of the air in the cylinder must be constant. Therefore, the number of moles $n$ is a constant for both the initial and final states of the cylinder.

**Hint A.3 Relation between the initial and final states**

From the ideal gas equation, after a little algebraic manipulation, we get $pV = nRT$. This will be true in both the final and initial states of the cylinder, and, as explained in the previous hint, since $n$ is constant, the two states are related by

$$\frac{p_i V_i}{T_i} = \frac{p_f V_f}{T_f}.$$

**Hint A.4 Gauge pressure**

Recall that the gauge pressure is the difference between the absolute pressure and the atmospheric pressure (i.e., $1.0 \times 10^5$ Pa). Thus, if you measure a gauge pressure $p_g$, then the absolute pressure $p$ is given by

$$p = p_g + p_a,$$

where $p_a$ is the atmospheric pressure.

**ANSWER:**

$T_f = 503°C$
The increase in gas temperature caused by this compression stroke is one of the reasons why a car engine gets so hot when it is running.

Problem 16.42
On average, each person in the industrialized world is responsible for the emission of 10,000 kg of carbon dioxide (CO₂) every year. This includes CO₂ that you generate directly, by burning fossil fuels to operate your car or your furnace, as well as CO₂ generated on your behalf by electric generating stations and manufacturing plants. CO₂ is a greenhouse gas that contributes to global warming.

Part A
If you were to store your yearly CO₂ emissions in a cube at STP, how long would each edge of the cube be?

ANSWER: 17.2 m

Problem 16.47
On a cool morning, when the temperature is 16.0 °C, you measure the pressure in your car tires to be 30.0 psi. After driving 48.0 mi on the freeway, the temperature of your tires is 48.0 °C.

Part A
What pressure will your tire gauge now show?

ANSWER: 34.9 psi

Problem 16.56
8.0 g of helium gas follows the process 1 → 2 → 3 shown in the figure.

Part A
Find the value of V₁.

ANSWER: 25.4 L

Part B
Find the value of V₂.

ANSWER: 76.3 L

Part C
Find the value of p₂.

ANSWER: 6.00 atm

Part D
Find the value of T₁.

ANSWER: 657 °C

Problem 16.69
The 50 kg circular lead piston shown in the figure floats on 0.190 mol of compressed air.
Part A
What is the piston height \( h \) if the temperature is 30°C?

**ANSWER:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>37.2 cm</td>
<td>Correct</td>
</tr>
</tbody>
</table>

Part B
How far does the piston move if the temperature is increased by 200°C?

**ANSWER:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>24.6 cm</td>
<td>Correct</td>
</tr>
</tbody>
</table>

**Score Summary:**
Your score on this assignment is 100.9%.
You received 41.94 out of a possible total of 50 points, plus 8.51 points of extra credit.