Workshop Tutorials for Introductory Physics

Solutions to TI5: **Kinetic Theory**

A. Review of Basic Ideas:

Kinetic Theory

Properties of materials can be described at the **macroscopic** level, which we can see and measure easily or at the microscopic level where special equipment is needed to observe what is happening to atoms and **molecules**. For example, the pressure of a gas can be described as the **force** per unit area exerted by the gas on a surface or can be thought of as the **momentum** imparted to the surface by the molecules of the gas. Similarly we can talk of the temperature of a gas and measure it with a thermometer or we can say the temperature of a gas is determined by the average **kinetic** energy of the gas molecules.

Kinetic theory describes the properties of gases at the molecular level. In particular it describes the temperature, T, pressure, P, and volume, V, of a gas and how they are related. For an ideal gas - one where there is no attraction between the molecules - it can be shown that $\boldsymbol{PV = nRT}$ where n represents the number of moles of gas and R is the universal gas constant. One **mole** contains 6.023×10^{24} molecules of gas. It is interesting to note that this equation does not depend on the type of molecule, but rather on the **number** of molecules present.

Real gases can be considered as ideal when the density of the gas is low enough so that attraction between the molecules is negligible. The equation above shows us that if we keep the volume constant and **increase** the temperature then the pressure will increase. We can think about this at the molecular level. Increasing the temperature increases the average kinetic of the molecules, so when they collide with the surfaces of the container we would expect to see a greater change in momentum as they reverse direction. Hence the **pressure** is greater.

Kinetic theory can also explain why evaporation from your skin (perspiration) helps you stay cool. Those molecules with the greatest **kinetic energy** are more likely to escape from your body thus reducing the average kinetic energy of those left behind, thus reducing your temperature.

B. Activity Questions:

1. 2D model of gases

When you increase the "temperature" of the gas the molecules move faster, they have an increased velocity. This means that when they collide with the lid (and walls) of the container they exert a greater pressure, as they can transfer more momentum to the lid. If the lid is not held in place, it will be pushed up, increasing the volume of the container.

2. Water boiling at less than 100°C

Boiling happens when evaporation occurs beneath the surface of a liquid, forming bubbles of gas which rise to the surface and escape. The pressure inside a bubble has to be equal to the pressure outside for the bubble to exist. The pressure outside the bubble depends on the temperature of the water. So boiling depends not only on temperature, but pressure as well. If you decrease the atmospheric pressure then the pressure required inside the bubble lowers and the molecules in the liquid don't need to move as fast to exert this pressure on the bubble. So the boiling point decreases.

When the syringe is pulled suddenly, the volume increases, so pressure decreases and boiling point decreases.

3. Blowing

When you blow on your hands to warm them you do so wit your mouth fairly open, and you puff on your hands, held close to your mouth. The air coming out of our mouth is at, or close to, body temperature, so it feels warm against your hands which are at a lower temperature.

When you blow on food or drink to cool it you purse your lips and blow a stream of air over it. As the air comes out of your mouth its volumes can expand as the pressure around it drops. As the volume increases the air cools, so it is cooler than body temperature, and quite a lot cooler than hot drink temperature. The flow of air helps increase cooling by convection.

4. Dropper

When you squeeze the rubber top on the dropper you squeeze the air out. Then when you put the tip into the liquid and stop squeezing the top, the low pressure inside sucks up the liquid. In fact it is the higher pressure outside the dropper, in the liquid, that pushes the liquid up into the dropper. The liquid is held in by the lower pressure in the tube than the external atmospheric pressure.

5. Boyle's law.

Hopefully your results agree with Boyle's law, which states that volume varies inversely with pressure, ($P \propto \frac{1}{V}$) however there may be small differences due to experimental error.

C. Qualitative Questions.

1. Two equal-sized rooms communicate through an open doorway. However, the average temperatures in the two rooms are maintained at different values.

a. The rooms are of equal volume and must have equal pressures, otherwise air would rush from one room to the other. One room is being maintained at a higher temperature, so using $PV = nRT$, this room must have a smaller number of air molecules, n, if T is greater but PV is the same.

b. Temperature is a measure of average kinetic energy, hence the molecules in the room with lower temperature will have lower average kinetic energy and lower average speeds.

2. Brent has bought Rebecca a new pressure cooker for her birthday.

a. Food cooks faster in a pressure cooker than in a saucepan because the pressure is much higher, hence the temperature can be higher. In a saucepan, even with the lid on, the pressure cannot exceed atmospheric pressure by very much. When a liquid boils, bubbles are formed beneath the surface of the liquid. The pressure within a bubble has to be equal to that of the atmosphere plus the water above for the bubble to exist. The pressure outside the bubble depends on the temperature of the water. So boiling depends on temperature, and pressure. If you increase the pressure then the pressure required inside the bubble increases and the temperature needed to make the liquid boil increases. So the boiling point increases, and the food is cooked at a higher temperature, hence it cooks faster.

b. The casserole will be hotter than one from a saucepan. A normal saucepan with water (or a water based food in it), can only get to 100^{o}C. At this temperature, any extra heat (thermal energy) that goes from the hotplate into the pan goes to changing the state of the water into steam. In a pressure cooker the temperature can get much hotter, as the water inside boils at a higher temperature, so much more heat can be added, increasing temperature rather than breaking bonds to change state. Pressure cookers typically cook at around 120 ^{o}C, which is also hot enough to kill many nasty bacteria such as botulism.

D. Quantitative questions.

The case has a volume of 8 litres ($= 8 \times 10^{-3}$ m^3) of N_2 gas at atmospheric pressure, at $T = 8^{o}C = 291$ K. The next day $T = 35^{o}C = 308$ K and enough nitrogen escapes so that $P = 1$ atm $= 100$ kPa again. That evening, when the temperature has dropped back to 8^{o}C again, the pressure inside the case is measured.

a. Using $PV = nRT$, we get:

$n_{\text{next day}} = PV/RT = (1.0 \times 10^5 \text{ Pa} \times 8 \times 10^{-3} \text{ m}^3) / (8.31 \text{ J.mol}^{-1}.\text{K}^{-1} \times 308 \text{ K}) = 0.31$ mol

0.31 mole $= 0.31 \times 28$ g.mole^{-1} $= 8.8$ g of N_2 gas.

b. We need to know how much was originally there to know how much was lost:

$n_{\text{initial}} = PV/RT = (1.0 \times 10^5 \text{ Pa} \times 8 \times 10^{-3} \text{ m}^3) / (8.31 \text{ J.mol}^{-1}.\text{K}^{-1} \times 281 \text{ K}) = 0.34$ mol,

hence 0.34 mole – 0.31 mole = 0.03 moles was lost. This is equivalent to 0.84 g. This is how much will need to be put back in to refill the case.

c. We know that $n_{\text{final}} = n_{\text{next day}}$ because the leak was fixed, so we can now find P_{final} :

$P = nRT/V = (0.31 \text{ mole} \times 8.31 \text{ J.mol}^{-1}.\text{K}^{-1} \times 281 \text{ K}) / (8 \times 10^{-3} \text{ m}^3) = 9.0 \times 10^4 \text{ Pa} = 90 \text{ kPa} = 0.9$ atm.