3.10 Heating Curves

Objective

In this experiment, you will gather temperature vs. time data and construct a heating curve for deionized water and a heating curve for a sodium chloride solution. By analyzing the data, you will also calculate the energy output of the hot plate used in the experiment.

Background

At the molecular level, the components of all matter are in constant motion and are under the influence of intermolecular forces. The phase of a sample of matter depends on the level of motion of its molecules and the strength of its intermolecular forces. In the solid phase, no translational motion exists, but the molecules vibrate in place; the kinetic energy of the molecules is not enough to overcome the strength of the intermolecular forces. In the liquid phase, the molecules roll and tumble around each other as they move through space; the kinetic energy of the molecules is about equal to or slightly greater than that of the intermolecular forces. Finally, in the gas phase, the molecules move through space at high speed and achieve great distances between themselves; the kinetic energy of the molecules greatly exceeds the strength of the intermolecular forces.

Phase changes can be initiated by introducing a source of energy (usually in the form of heat) to a sample of matter. The sample of matter absorbs the heat which results in energy changes of the molecules. A heating curve shows how the temperature of a sample of matter changes as a function of time or added heat as shown in Figure 3.14.

![Heating Curve](image)

Figure 3.14: General shape of a heating curve for a sample of matter.

Looking at the general shape of the heating curve, we see that there are sloped regions and flat regions. The sloped regions make sense; as heat is added, the temperature increases. As you recall, temperature is a measure of the average kinetic energy of the molecules, so we can
conclude that in the sloping regions, the heat absorbed by the sample of matter is being used to increase the kinetic energy of the molecules, i.e. the molecules are moving faster and faster. The flat regions require more analysis. In these flat regions, the molecules are absorbing heat energy, but they are NOT using it to move faster, so the kinetic energy is NOT increasing. Therefore, the potential energy must be increasing!

In this situation, the most useful definition of potential energy is the energy due to position. In any sample of matter, intermolecular forces exist which work to keep molecules close together. Thinking about relative positions of molecules in the phases of matter, we see that molecules are very close in solids, a little further apart in liquids, and very far apart in gases. Relating this knowledge back to the flat regions in the heating curve and the definition of potential energy, we can conclude that when the heat energy is not being used to increase the kinetic energy of the molecules, it is being used to increase the potential energy of the molecules by changing how far apart they are from one another. Specifically, the heat energy is being used to precipitate a change of state. One interesting note is that the temperature of the sample of matter will not increase until the phase change is complete.

In addition to obtaining experimental heating curves, you will determine the energy output of a hot plate. This analysis can be done by calculating the heat needed to increase the temperature of your sample of water from 0 °C to 100 °C and dividing by the time. The equation needed to calculate the necessary heat is:

\[ q = mC_s\Delta T \]

In this equation, \( q \) is the heat, \( m \) is the mass, \( C_s \) is the specific heat capacity (4.184 J/g·K for water), and \( \Delta T \) is the change in temperature.

In the second part of the experiment, you will be producing a heating curve for a salt water solution. You will see that the addition of salt will depress the freezing point and elevate the boiling point; these are examples of colligative properties. The freezing point depression and boiling point elevation can be calculated with the two formulas below.

\[ \Delta T_f = imk_f \]

\[ \Delta T_b = imk_b \]

Note that these equations calculate the CHANGE in the freezing point and boiling point, not the actual temperatures at which freezing and boiling occur. In these equations, \( i \) is the van’t Hoff factor, \( m \) is the molality, \( k_f \) is the freezing constant of the pure liquid, and \( k_b \) is the boiling constant for the pure liquid. Note that for water, \( k_f = 1.86 \, ^\circ C/m \) and \( k_b = 0.51 \, ^\circ C/m \).

Since colligative properties depend on the number or particles in solution, not their identity, the van’t Hoff factor is necessary when performing calculations involving ionic compounds dissolved in water. Theoretically, ionic compounds dissociate completely in water, but often this is not the case due to the formation of ion pairs. In an ion pair, two oppositely-charged ions travel together as one closely-associated unit. For example, sodium chloride has a theoretical van’t Hoff factor of 2 (because it theoretically dissociates into two ions, Na\(^+\) and Cl\(^-\)), but in a
0.05 \text{ m} \text{ solution}, \text{ the van’t Hoff factor is 1.9. As another example, potassium sulfate, K}_2\text{SO}_4, \text{ has a theoretical van’t Hoff factor of 3, but an actual value of 2.6 in a 0.05 \text{ m} \text{ solution.}}$

\textbf{Procedure}

\textbf{Heating Curve of Water}

1. Obtain and wear goggles.

2. Prepare the computer for data collection by navigating through the Experiment folder to the Chemistry with Computers folder of Logger Pro and selecting the “10_Heating_Curves.cml” file. The vertical axis has temperature scaled from -10 to 110 °C. The horizontal axis has time scaled from 0 to 1500 seconds. You will only need a temperature probe for this experiment.

3. Add approximately 150 mL of deionized water into a 250-mL beaker.

4. Add enough ice to the water in the 250-mL beaker to form a slush then add a magnetic stirrer.

5. Place the temperature probe into the slush.

6. Wait at least 5 minutes to allow the slush to come to thermal equilibrium.

7. The hot plate needs to be pre-heated to ensure a steady flow of heat is used in the experiment. Turn the hot plate on and set it to “6.” Let it heat for 5 minutes.

8. Wipe the bottom of the beaker dry then place it on the hot plate. Use a ring stand and clamp to hold the temperature probe so that it’s at least half way up from the bottom of the beaker. The temperature probe should be near the spout of the beaker.

9. Cover the beaker with a watch glass.

10. Turn on the magnetic stirrer and adjust the setting so that the water does not splash, between 3 and 4.

11. Begin the data collection on Logger Pro. Temperature readings will be recorded every 20 seconds.

12. After the water begins to boil rapidly, the curve will flatten out and the temperature should remain fairly steady. Collect at least five additional temperature readings of this portion of the curve.

13. Stop the data collection and remove the beaker from the hot plate to allow it to cool.

14. Select “Examine” under the “Analyze” drop-down menu. A vertical line will appear that will allow you to examine individual data points.
15. Move the vertical line to the point on the graph where the temperature begins to increase steadily (this should be at the end of the initial flat portion of the curve). Record the temperature and time of this data point, referring to them as $T_i$ and $t_i$, respectively.

16. Move the vertical line to the point of the graph where the temperature stops increasing steadily (this should be right before the flat portion of the curve near the end of the graph). Record the temperature and time of this data point, referring to them as $T_f$ and $t_f$, respectively.

17. Change the generic title of the graph to something more specific. Print a landscape copy of the Graph window by selecting Print Graph under the File menu. To print landscape, select Page Setup under the File menu before printing. Enter your name(s) and the number of copies of the graph you want.

18. After the water has cooled to room temperature, measure its mass. You want the mass of just the water, NOT the water and the 250-mL beaker together!

**Heating Curve of a NaCl Solution**

Repeat the same procedure as before, except dissolve 5.0 grams of NaCl in the 150 mL of deionized water before adding ice.

**Results and Calculations**

1. Calculate the heat output of the hot plate by first calculating the heat necessary (using the $q$ equation) to change the temperature of your water sample from $T_i$ to $T_f$. Divide this value by the time it took for the water sample to do this temperature change ($t_f - t_i$).

2. Using this value for the heat output, calculate the heat used for the sloping region in the heating curve for the sodium chloride solution. Do this by multiplying the heat output of the hot plate by the quantity ($t_f - t_i$) from your NaCl heating curve. This heat should be different than the heat you calculated for the water sample via the $q$ equation. Can the difference be attributed solely to the freezing point depression and boiling point elevation, or is the difference greater or less than that? (HINT: Calculate $q$ for the sodium chloride solution using its $T_i$ and $T_f$ to help answer this question.)

3. Assuming complete dissociation of NaCl, calculate the theoretical freezing point depression and boiling point elevation for the NaCl solution.

**Discussion**

In your Discussion be sure to talk about your results from the calculations and any other standard items as indicated by your instructor. Additionally, address the following topics.

- The differences between the two heating curves.
• How closely the theoretical freezing point depression and boiling point elevation match the experimental values. If they are different, give possible explanations as to why.