Physical Properties:

Determination of the Molar Mass of a Solute using Freezing-Point Depression

Purpose

The purpose of this experiment is to determine the molar mass of a solute by measuring the freezing-point of a solution.

Learning Objectives

Prepare a cooling curve by collecting temperature data as a solvent is cooled until it freezes.

Prepare a cooling curve by collect temperature data of a solution in the same solvent as the solution is cooled until it freezes.

Determine the freezing point of the solvent and the solution from cooling curves.

Calculate the molar mass of the solute using the freezing-point depression data.

Laboratory Skills

Use a thermometer.

Use a hot plate.

Use a balance.

Equipment

- large test tubes
- stopwatch or smart phone
- copper wire stirring loops
- hot plates

Chemicals

- Stearic acid
- Biphenyl
- Bromochlorobenzene
- Naphthalene
- Anthracene

Introduction

Some physical properties of solutions are different from those of the pure solvent. The magnitude of these changes in physical properties is proportional to the number of solute particles contained in the solution. Collectively, these physical properties are called **colligative properties**. They include freezing point, boiling point, vapor pressure, and osmotic pressure.

In general, solutions freeze at a lower temperature than the pure solvent. The difference between the freezing point of a solution and the freezing point of the pure solvent, the change in freezing point, is referred to as the freezing-point depression, ΔT_f, and is defined according to Equation FPD.1:

$$\Delta T_\mathrm{f} = T_\mathrm{f}(\text{solvent}) - T_\mathrm{f}(\text{solution}) \qquad \text{(Equation FPD.1)}$$

Freezing point is a colligative property, so the freezing-point depression is proportional to the number of solute *particles* contained in solution. For nonelectrolytes, the number of solute particles contained in solution is proportional to the *molality* of solute. Therefore, the freezing-point depression will be proportional to the molality of solute, as shown in Equation FPD.2

$$\Delta T_\mathrm{f} = K_\mathrm{f} m_\text{solute} \qquad \text{(Equation FPD.2)}$$

The proportionality constant, K_f, is the **molal freezing-point-depression constant**. Its value depends on the *identity* of the solvent. For water, the value of K_f is 1.86°C/m. For each mole of solute added per kilogram of pure water, the freezing point is lowered by 1.86°C.

The relationship between freezing-point depression and molality can be used in several ways. For a solution of known molality, the freezing-point depression may be measured experimentally to determine the value of K_f using Equation FPD.3:

$$K_\mathrm{f} = \frac{\Delta T_\mathrm{f}}{m_\text{solute}} \qquad \text{(Equation FPD.3)}$$

Freezing-point depression may also be used to determine the molar mass of a solute provided that the mass of the solute and solvent and the freezing-point depression constant, K_f, is known for the solvent. By measuring the freezing point of the solution, the molality of the solute can be calculated by solving the freezing-point depression equation above for molality of solute using Equation FPD.4:

$$m_\text{solute} = \frac{\Delta T_\mathrm{f}}{K_\mathrm{f}} \qquad \text{(Equation FPD.4)}$$

Next, the number of moles of solute may be calculated by multiplying the molality of the solute by the mass of solvent in kilogram using Equation FPD.5:

$$\text{mol solute} = m_\text{solute} \times \text{kg solvent} \qquad \text{(Equation FPD.5)}$$

Please note that this equation has the mass of solvent only. The molar mass of the solute (MM_{solute}) may then be calculated by dividing the mass of solute by the number of moles of solute using Equation FPD.6:

$$MM_{solute} = \frac{\text{g solute}}{\text{mol solute}} \qquad \text{(Equation FPD.6)}$$

The freezing point of both the solvent and the solution will be determined by heating the substance to a temperature that is above the freezing point. Then, the substance will be allowed to cool. While it cools, the temperature of the substance will be measured every 30 seconds. A plot of temperature (vertical axis) versus time (horizontal axis) will be made from the data to give what is called a **cooling curve**. This curve is the reverse of a **heating curve**, which is more commonly discussed in chemistry texts. In the left-most part of Figure FPD.1, region A, water is a solid (ice) at -40 degrees.

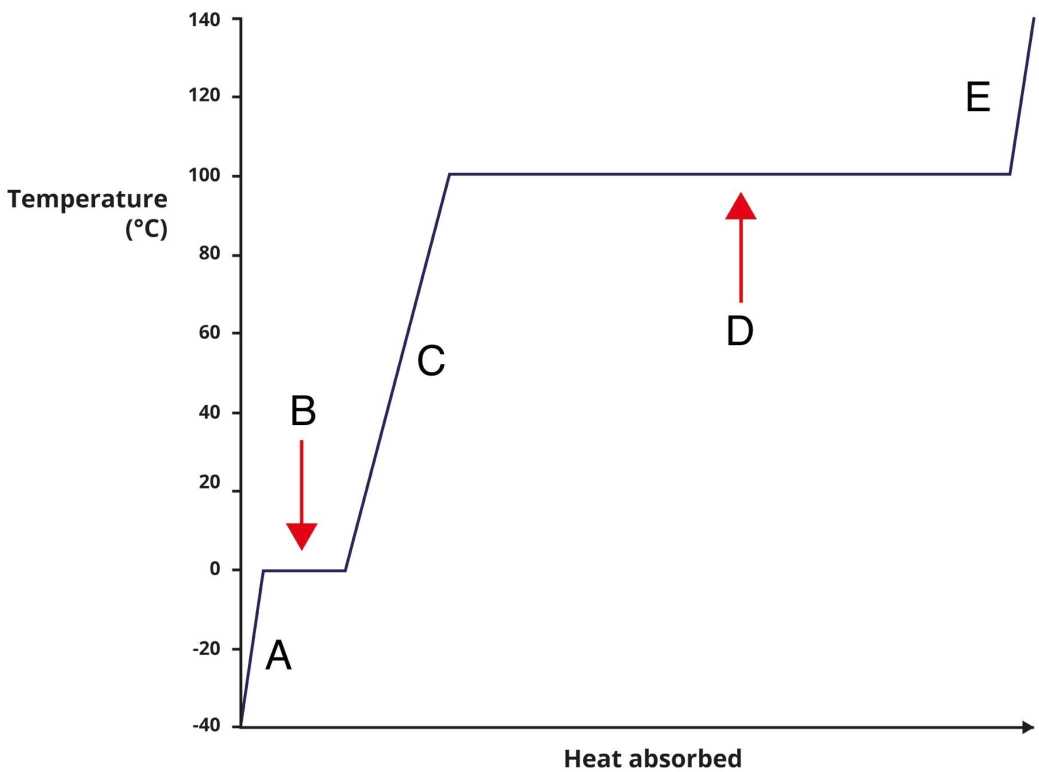


Figure FPD.1: Heating Curve for water showing temperature and phase changes as heat is added.

As heat is added, the temperature rises, but the ice remains a solid until the melting point is reached. In region B, heat is added but the temperature remains constant until the sample has completely melted. As heat continues to be added (region C), the temperature of the liquid water rises until the boiling point is reached. At this point (region D) the temperature remains constant even as heat is added, until the entire sample has become water vapor. In region E, heat continues to be added and the temperature of the water vapor increases. For any pure substance, the temperature does not change while the substance is undergoing a phase change. The heating curve has a slope of 0 (is flat) during the phase changes, shown in regions B and D in Figure FPD.1. The same is true for the cooling curve of a pure substance (solvent). While the solvent is freezing, the temperature will not change. However, when a solution cools, its temperature drops at a particular rate and when it freezes, the temperature will continue to change but at much slower rate than the liquid cooled.

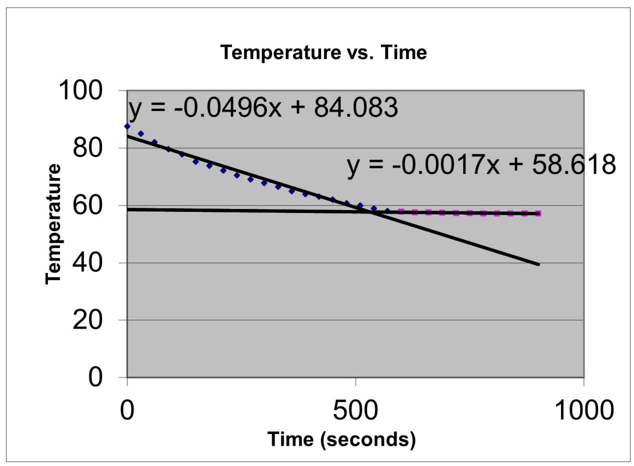
Table FPD.1 contains temperature versus time data for the cooling of a solvent and a solution made from the solvent. The temperature at the beginning drops a substantial amount between readings, more than 0.5°C. Later, the temperature drops much less between readings, less than 0.5°C. It is during this second period of time, when the temperature drops more slowly, that the substance is freezing.

Table FPD.1: Temperature vs. Time Data for the Cooling of a Solvent and a Solution

Time (s)	Temperature of Solvent (°C)	Temperature of Solution (°C)	Time (s)	Temperature of Solvent (°C)	Temperature of Solution (°C)
0	87.5	85.5	450	62.0	61.6
30	85.0	83.0	480	60.8	60.5
60	82.0	80.1	510	60.0	59.8
90	79.6	78.8	540	59.0	59.0
120	77.8	75.8	570	58.0	58.0
150	75.3	74.2	600	57.8	57.1
180	73.8	72.5	630	57.5	56.4
210	72.2	71.0	660	57.5	55.8
240	70.5	69.8	690	57.5	55.2
270	69.1	68.1	720	57.4	55.0
300	67.8	67.0	750	57.3	55.0
330	66.5	66.0	780	57.3	55.0
360	65.0	64.	810	57.2	55.0
390	64.0	63.6	840	57.2	55.0
420	63.0	62.6	870	57.2	55.0
			900	57.2	55.0

Students will determine the freezing point by making a plot of temperature versus time and fitting two straight lines to the data. This is done by splitting the temperature data into two columns in Excel. The first column will be the temperature readings in which the difference between successive readings is greater than 0.5°C. The second column will be the temperature readings in which the difference between successive readings is less than 0.5°C. For the temperature data for the solvent, the spreadsheet would look like that shown in Figure FPD.2.

Time	Temperature	Temperature
0	87.5	
30	85	
60	82	
90	79.6	
120	77.8	
150	75.3	
180	73.8	
210	72.2	
240	70.5	
270	69.1	
300	67.8	
330	66.5	
360	65	
390	64	
420	63	
450	62	
480	60.8	
510	60	
540	59	
570	58	
600		57.8
630		57.5
660		57.5
690		57.4
720		57.3
750		57.3
780		57.2
810		57.2
840		57.2
870		57.2
900		57.2



A B

Figure FPD.2: A. Spreadsheet example for solvent temperature vs. time data B.Cooling curve constructed from the spreadsheet data.

Students will then construct a cooling curve plot by selecting all three columns (time plus the two temperatures) and proceeding to graph the data. Choose "XY plot" for the type of plot and choose the sub-option with just the data points on it (no lines connecting the dots). When the plot is made, it should look like the graph in Figure FPD.2 without the straight lines (trendlines).

Next, students will add trendlines to each set of data using the "Add trendline" option under the Chart menu. When adding the trendline, there are two "Temperatures" under the "Based on series" box. Click on the first "Temperature". Go to the next page and click on "display equation" and click "OK". Then, add the second line by using the “Add trendline” option again. This time, choose the second “Temperature” under the “Based on series” box. Don’t forget to click on “display equation.” The result should be a plot that looks something like the plot in Figure FPD.2. The freezing point will be determined by finding the temperature at which the two lines intersect. This can be done using algebra as seen in Example FPD.1:

Example FPD.1: Solving for the intersection point

Using the equations in FigureFigure FPD.2, the time at which the two equations meet can be determined by setting the two equations equal to each other and solving for “x”:

$$-0.0496x + 84.1 = -0.0017x + 58.6$$

$$25.5 = 0.0479x$$

$$x = \frac{25.5}{0.0479} = 532\,\text{s}$$

Then, the temperature at which the two lines intersect can be determined by placing $x = 532\,\text{s}$ into either equation, and calculating the value of y:

$$y = -0.0496\,(532) + 84.1$$

$$y = 57.7°\text{C}$$

The freezing point of the solvent is determined to be 57.7°C.

Procedure

Collecting the Data

1. Fill your 400 mL beaker about 3/4 full with DI water. Place several boiling stones in the water and place the beaker with the water on a hot plate.

2. Start heating the water to boiling using a mid-scale setting on the hot plate.

3. While the water bath is heating, stand up a test tube in your 30 mL beaker and weigh both to the nearest 0.001 g. Record the weight on your data sheet.

4. Add about 9 grams of stearic acid to the test tube and weigh the test tube, stearic acid and beaker to the nearest 0.001 g. Record the weight on your data sheet.

5. Determine the mass of stearic acid using difference methods.

6. Place the test tube with the stearic acid in your water bath and heat it until it is a liquid at 85°C.

7. While you are waiting for the stearic acid to melt, crumple up 2 sheets of paper towels and place them in your 250 mL beaker for insulation while your molten stearic acid cools. There should be enough room in the beaker with paper towels for the test tube to fit snugly into.

8. When the temperature of the molten stearic acid reaches 85°C, take the test tube out of the water bath and place it in the 250 mL beaker with the paper towels. Take a temperature reading to the nearest 0.1°C while you start your stopwatch and record your reading as time 0 in Report Table FPD.1.

9. The molten stearic acid should be stirred gently with a wire loop while cooling to prevent supercooling. Continue to take a temperature reading to the nearest 0.1°C for about 15 minutes while you fill in the data table.

10. During the last 5 minutes, the temperature difference between readings should be less than 0.5°C and the substance should start freezing out (the solution will get cloudy). If the substance does not start freezing out in the first 15 minutes, you may need to cool for a longer period of time.

11. Obtain an unknown compound and record its number on your data sheet.

12. Weigh out approximately 1 gram to the nearest 0.01 g and record the mass on your data sheet.

13. Add the unknown compound to the test tube containing the stearic acid.

14. Place the mixture in the hot water bath and heat it until its temperature reaches 85°C.

15. Stir the molten mixture and repeat the above procedure used for pure stearic acid for the solution of the unknown and stearic acid.

Analyzing the Data

1. Make 2 plots of cooling curves using Excel. Each cooling curve is a plot of temperature (vertical axis) versus time (horizontal axis). Following the procedure given in the introduction, the first cooling curve gives you the freezing point of pure stearic acid and the second cooling curve provides the freezing point of the solution of the unknown plus stearic acid.

2. Determine the freezing-point depression from the difference between the freezing point of pure stearic acid and the solution freezing point:

$$\Delta T_\mathrm{f} = T_\mathrm{f}(\text{solvent}) - T_\mathrm{f}(\text{solution}) \qquad \text{(Equation FPD.1, revisited)}$$

3. Divide the freezing-point depression by the K_f value of stearic acid, which is 4.5°C kg/mol, to obtain the molality of the solute in the solution.

$$m_\text{solute} = \frac{\Delta T_\mathrm{f}}{K_\mathrm{f}} \qquad \text{(Equation FPD.4, revisited)}$$

$$m_\text{solute} = \frac{\Delta T_\mathrm{f}}{4.5\ \text{kg/mol}}$$

4. Multiply the calculated molality by the number of kilograms of stearic acid to determine the moles of solute.

$$\text{mol solute} = m_\text{solute} \times \text{kg solvent} \qquad \text{(Equation FPD.5, revisited)}$$

5. Divide the mass of solute in grams by the number of moles of solute to calculate the molar mass of the solute (MM_solute).

$$MM_\text{solute} = \frac{\text{g solute}}{\text{mol solute}} \qquad \text{(Equation FPD.6, revisited)}$$

Collecting the Data

Freezing Point of Solvent

Mass of test tube + beaker (g) ____________

Mass of test tube + beaker + stearic acid (g) ____________

Mass of stearic acid (g) ____________

Report Table FPD.1: Time and Temperature Data: Freezing Point of Solvent (Stearic Acid)

Time (s)	Temperature (°C)	Time (s)	Temperature (°C)	Time (s)	Temperature (°C)
0		330		660	
30		360		690	
60		390		720	
90		420		750	
120		450		780	
150		480		810	
180		510		840	
210		540		870	
240		570		900	
270		600			
300		630			

Freezing Point of Solution

Unknown number ________________

Mass of unknown used (g) ________________

Report Table FPD.2: Time and Temperature Data: Freezing Point of Solution

Time (s)	Temperature (°C)	Time (s)	Temperature (°C)	Time (s)	Temperature (°C)
0	________	330	________	660	________
30	________	360	________	690	________
60	________	390	________	720	________
90	________	420	________	750	________
120	________	450	________	780	________
150	________	480	________	810	________
180	________	510	________	840	________
210	________	540	________	870	________
240	________	570	________	900	________
270	________	600	________		
300	________	630	________		

Analyzing the Data

Freezing Point of the Solvent

Time at which 2 lines intersect ________________

Show calculations here:

Freezing point of solvent from 1st cooling curve ________________

Show calculations here:

Calculating Molar Mass

Molality of unknown in solution ______________

Show calculations here:

Moles of unknown in solution ______________

Show calculations here:

Molar mass of unknown ______________

Show calculations here: