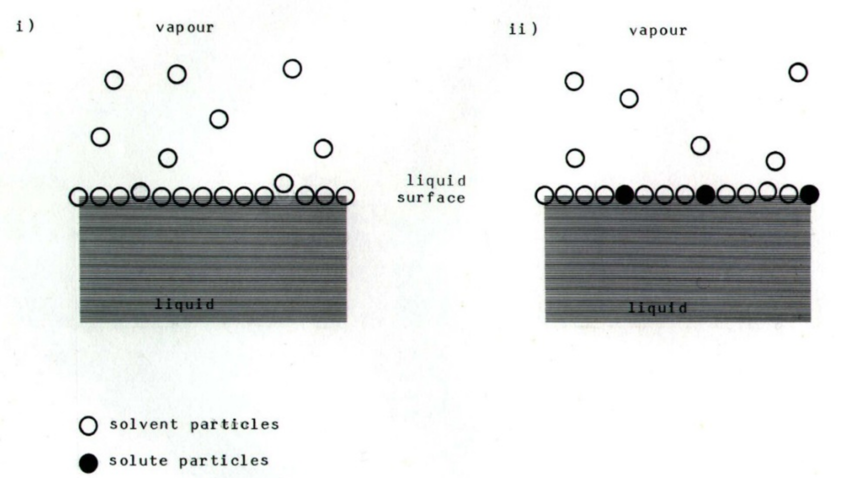
Colligative Properties: Freezing Point Depression

Introduction

The properties of a pure solvent may be altered when a solute is dissolved in it. The magnitude of the change is proportional to the amount of solute added. Some properties of the solvent are changed only by the number of solute particles present, without regard to the particular nature of the solute. These properties are called colligative properties of the solution. Examples of colligative properties include changes in vapor pressure, boiling point, freezing point and osmotic pressure.[1]

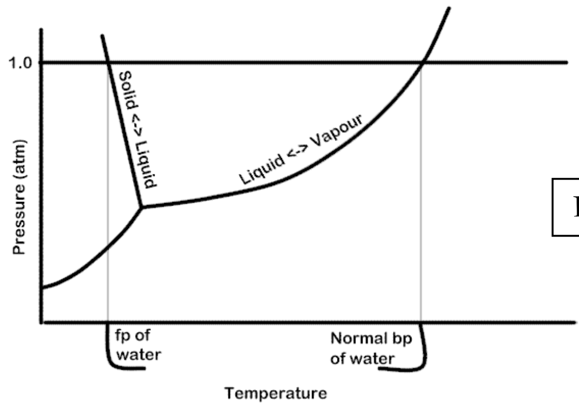
When a nonionizing, nonvolatile solute is added to a volatile solvent, the amount of solvent that can escape from the surface of the liquid at a given temperature is lowered, relative to the case where only the pure solvent is present. Thus the vapor pressure above the solution containing solute will be lower than the vapor pressure of the pure solvent. The dissolved solute molecules physically block the surface of the solvent, preventing some of the solvent molecules from evaporating at a given temperature.

FIG. A3.2. Vapourisation of i) a pure solvent and ii) the same solvent containing a non-volatile solute

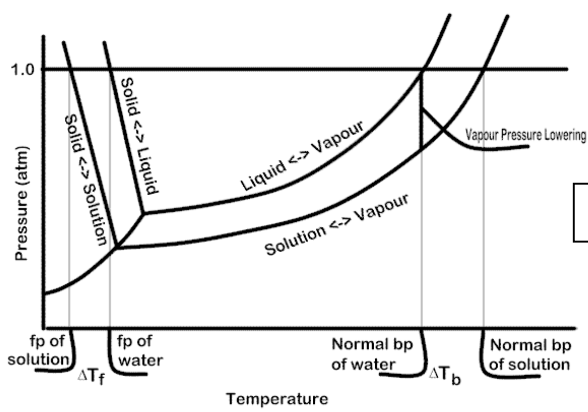


Shown below are two phase diagrams for water. The first diagram illustrates the normal freezing and boiling points for pure water, i.e., without the addition of any nonvolatile solute. The second diagram illustrates the increased boiling point and reduced freezing point for water after the addition of a solute.

[1] This is why ethylene glycol works as antifreeze in your car's cooling system: it depresses the freezing point of water so the coolant does not freeze during the winter months.



Phase diagram: Pure water, no solute present



Phase diagram: Solute dissolved in water

The decrease in freezing point or the increase in boiling point is proportional to the molal concentration m (molality):

$$\Delta T = K \cdot m_s$$

We will refer to this equation as the colligative property equation

ΔT = either decrease in freezing point or increase in boiling point of solvent
K = either freezing point or boiling point constant for given solvent

m_s = molality = moles of solute/kg of solvent

Remember K is a constant for a given solvent and represents by how many degrees the freezing point will change when 1.0 mols of solute is dissolved per kilogram of solvent. For example, let's suppose you are investigating the freezing point depression of water. The colligative property equation would take the following form:

$$\Delta T_f = K_f \cdot m_s$$

where $\Delta T_f = T_{pure\ solvent} - T_{solution}$

In this case K = K_f, the freezing point depression constant for water which is 1.86 °C kg mol^{-1}. Similarly, if you are investigating the boiling point elevation of water, the colligative property equation would take the form:

$$\Delta T_b = K_b \cdot m_s$$

where $\Delta T_b = T_{solution} - T_{pure\ solvent}$

In this case K = K_b, the boiling point elevation constant for water which is 0.51 °C kg mol^{-1}.

Purpose

To become familiar with colligative properties and to use then to determine the freezing point depression constant of water and the molar mass of an unknown substance.

Approach

Water will serve as your solvent for this experiment. First you will determine the freezing point of pure water. You will then prepare a 0.500 m sucrose solution and determine its freezing point. Finally, you will determine the freezing point of a solution containing an unknown solute.

Because the presence of solute reduces the freezing point of an aqueous solution below 0°C, the freezing point of pure water, we need a way to cool the solutions below 0°C. To do this we will use the phenomenon itself to provide the conditions necessary for the test. We will make an ice/salt bath by mixing crushed ice with sodium chloride. The temperature of this ice/salt bath (~ -20°C) will be lower than the temperature of a pure ice bath (0°C).

Students work in pairs.

Apparatus/Materials

Centogram balance	Deionized water
Two large test tubes (24mm x 150 mm)	2 digital thermometers
1- 600 mL beaker	1 box of salt
Crushed ice	Sucrose
Stopwatch/timer	Stirrer

Part A: Preparation of 0.5 ***m*** sucrose solution

1. Determine the molar mass of sucrose.
2. Using clean glassware and a centigram balance, prepare 50.0 g of a 0.5 ***m*** sucrose solution.
3. Set solution aside for use in part C.

Continued on next page.

Part B: <u>Freezing Point of Pure Water</u>

Unlike the boiling point of water, which varies significantly with ambient local pressure, the freezing point of water is almost unaffected by pressure. Since thermometers may vary in accuracy, you will first calibrate your thermometer by using it to determine the freezing point of pure water.

1. Work with a partner to collect data. The analysis of the data is to be done individually.
2. Quarter fill a 600 mL beaker with crushed ice and pour a ½ inch layer of sodium chloride on top of the ice. Stir and thoroughly mix the ice and salt. Add another quarter layer of ice and pour another ½ inch layer on top of the ice. Stir and thoroughly mix the ice and salt.
3. Immerse a thermometer in the ice/salt bath, allow a minute for it to stabilize, and record the temperature of the ice/salt bath.
4. Half fill a test tube with water and insert a stirrer and thermometer into the test tube.
5. Carefully press the test tube down into the ice bath until the water is completely below the surface of the ice bath. Record the initial water temperature and start your timer.
6. Begin collecting time/temperature data every 30 seconds. Continue stirring the water as you collect data.
7. The temperature should "plateau" when the freezing process begins. Eventually the water will solidify to the point where you will be unable to stir it.
8. Continue taking the temperature of the water until after the temperature has dropped precipitously (by at least 1˚C) for 2 readings in a row after it had reached its plateau value.
9. Prepare a plot of your time/temperature data and determine your temperature correction factor.

Part C: <u>Freezing Point of 0.5***m*** Sucrose Solution</u>

1. Place the test tube containing the frozen water (with the stuck thermometer/stirrer) from Part A under hot water begin heating. Remove the thermometer and stirrer and dry the test tube.
2. Half fill the test tube with the 0.50 ***m*** sucrose solution prepared in Part A and insert a stirrer and thermometer into the test tube.
3. Carefully press the test tube down into the ice bath until the water is completely below the surface of the ice bath. Record the initial aqueous solution temperature and start your timer.
4. Begin collecting time/temperature data every 30 seconds. Continue to stir the solution as you collect data.
5. Continue recording the temperature every 30 seconds for the remainder of the freezing process. Remember that cooling curves for solutions often tend to show a more noticeable slope as opposed to a "plateau" when the freezing process begins. Eventually the solution will solidify to the point where you will be unable to stir it.
6. Continue taking the temperature of the solution until after the temperature has dropped precipitously (by at least 1˚C) for 2 readings in a row.

Part D: Molar Mass of Unknown Solute.

1. Weigh a large, clean, test tube to the nearest 0.01 g.
2. Fill the test tube about 2/3 full with DI water and weigh again. The difference in mass is the mass of the water.
3. Using weighing paper, weigh about 1.5 g of the unknown solute to the nearest 0.01 g.
4. Carefully add the unknown solute to the test tube and stir gently until dissolved.
5. Insert a stirrer and thermometer into the test tube.
6. Carefully press the test tube down into the ice bath until the water is completely below the surface of the ice bath. Record the initial aqueous solution temperature and start your timer.
7. Begin collecting time/temperature data every 30 seconds. Continue to stir the solution as you collect data.
8. Continue recording the temperature every 30 seconds for the remainder of the freezing process. Remember that cooling curves for solutions often tend to show a more noticeable slope as opposed to a "plateau" when the freezing process begins. Eventually the solution will solidify to the point where you will be unable to stir it.
9. Continue taking the temperature of the solution until after the temperature has dropped precipitously (by at least 1˚C) for 2 readings in a row.

Preparation of Finished Lab Report

Follow the steps below to prepare your finished lab report. Your report should contain the sections listed in the ***exact*** order they are listed below:

I) Title (front) page (typed)

a) Experiment title
b) Your name & name of your lab partner
c) Date experiment conducted
d) Chemistry 220, Canada College, Fall Session, 2014

II) Data (Excel spreadsheet format) (typed). Include data for your three temperature-time curves. The data should be in tabular form. DO NOT SPLIT UP DATA TABLES.[2]

a) Time-temperature data for pure water
b) Time-temperature data for 0.50 ***m*** sucrose solution (corrected)
c) Time-temperature data for unknown solute (corrected)

III) Cooling Curve Plots – Use Excel to generate cooling curve plots for each trial. For each plot, graph time on the x-axis and temperature on the y-axis. Properly label each plot. **You do not have to show linear equations for liquid and solid phases on these plots.**

[2] If you ran two trials show data for the trial that will be used in your calculations. If you ran two trials and determined an average value, then show data for both.

IV) Calculations (handwritten or typed)

Calculations: 0.5 *m* Sucrose Solution

1. Use the linear regression feature in Excel to determine a linear equation for the liquid phase and a linear equation for the solid phase for the 0.5 m sucrose solution. Solve these equations simultaneously to obtain the freezing point. [3]
2. Calculate the K_f value for water.
3. Compare your calculated K_f value to the published value and determine your % error.

Calculations: Unknown Solute

1. Use the linear regression feature in Excel to determine a linear equation for the liquid phase and a linear equation for the solid phase for the 0.5 m sucrose solution. Solve these equations simultaneously to obtain the freezing point.
2. Using the published K_f value for water, calculate the molality of the solution containing the unknown solute.
3. Calculate the molar mass of the unknown solute.

V) Data Summary (typed) – Prepare a table as shown below and enter results

Freezing pt. pure water (this is your temperature correction factor)	
Results for 0.5 m sucrose solution	
Linear equation (liquid phase) – 0.5 ***m*** sucrose	
Linear equation (solid phase) – 0.5 ***m*** sucrose	
Calculated freezing pt. for 0.5 ***m*** sucrose solution	
ΔT (0.5 ***m*** sucrose)	
Calculated K_f for water	
Published K_f value for pure water	1.86 °C/*m*
% error for K_f value (pure water)	
Results for unknown solute	
Mass of water	
Mass of unknown solute	
Linear equation (liquid phase) – unknown solute	
Linear equation (solid phase) – unknown solute	
Calculated freezing pt. for solution with unknown solute	
ΔT (solution with unknown solute)	
Published K_f value for pure water	1.86 °C/*m*
Calculated molality for unknown solute	
Calculated molar mass of unknown solute	

[3] You do not need to solve linear equations for the pure water freezing curve.

VI) Post Lab Questions (typed or hand written)

1. For a given number of moles of solute, why do ionic substances have a larger effect on the freezing and boiling points of solvents than do nonionic substances?

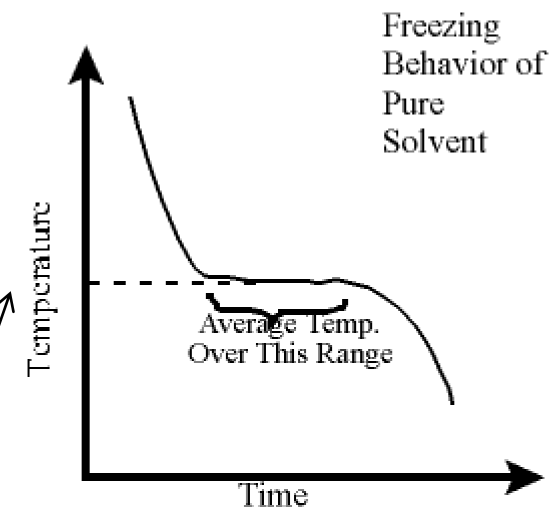
2. Which aqueous solution has the lower freezing point, 0.10 *m* NaCl or 0.10 *m* glucose? Explain your answer.

3. What mass of NaCl is dissolved in 200. g of water in a 0.100 m solution?

APPENDIX I – COOLING CURVES

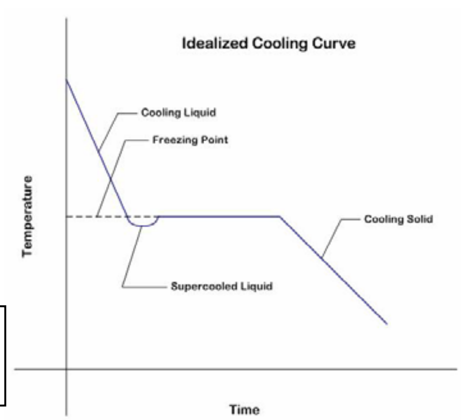
Determining a freezing point by visual observation is difficult, if not often impossible. For this reason a graphic method is employed.

Shown below is a typical cooling curve for a pure solvent, i.e., one that does not contain a nonvolatile solute. The cooling curve is generated by taking temperature readings of the cooling solvent at relatively short time intervals and then plotting these as a function of time.



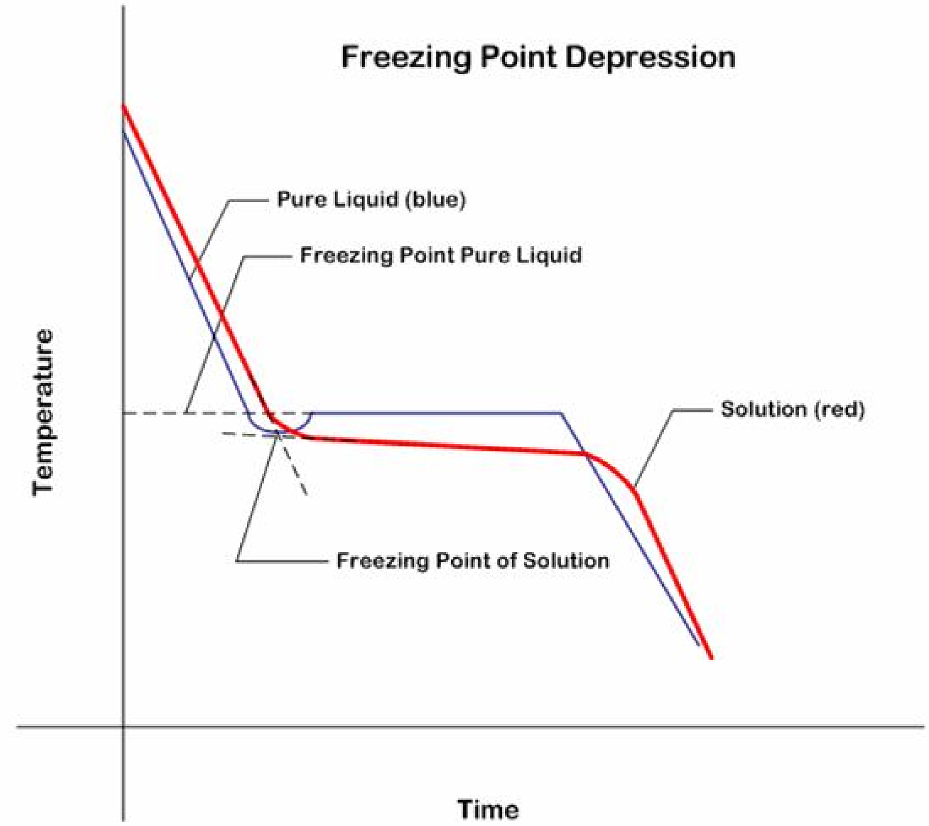
Freezing point for pure solvent.

The flat region represents the freezing point of the pure solvent. The freezing point temperature is determined by extrapolating a line to the y axis (Temperature). The value of T is then read off the y-axis. Sometimes pure liquids exhibit a phenomenon known as “super cooling” which occurs because the solution is cooling faster than the molecules can lock into position in a crystalline structure. Often, supercooling may be prevented by stirring the solvent.

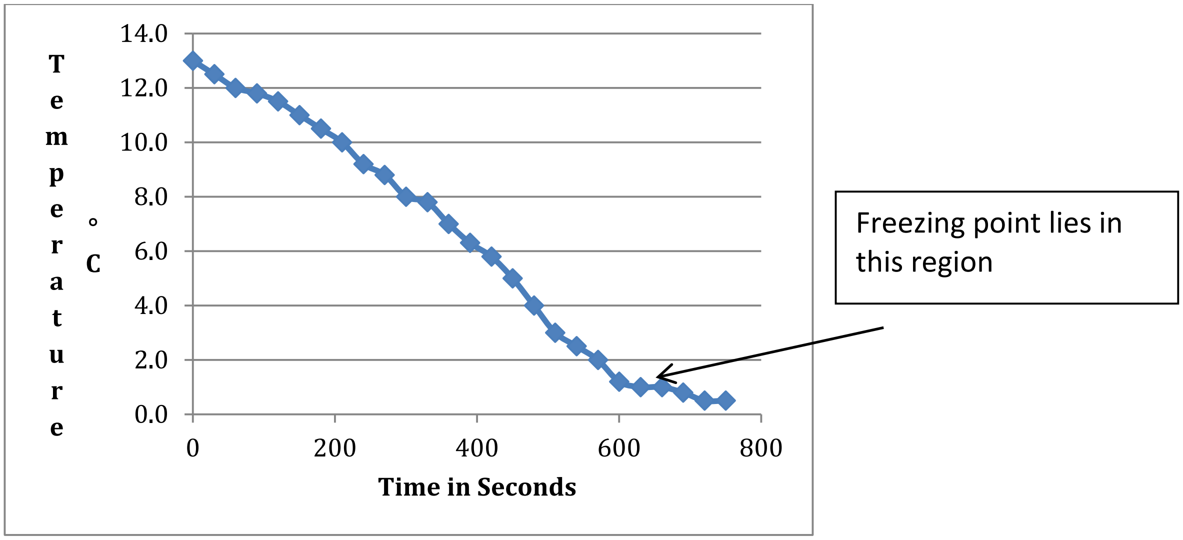


If supercooling occurs we still determine the FP by extrapolation

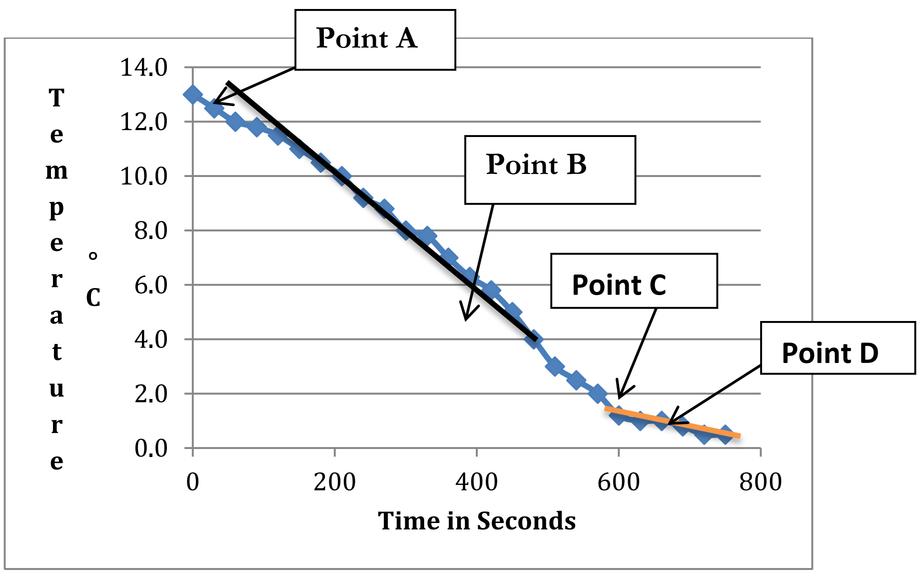
The shape of a cooling curve will change upon the addition of a nonvolatile solute to the solvent as shown in the figure below. The blue curve represents a cooling curve for a pure solvent exhibiting supercooling. The red curve represents a cooling curve for the same solvent to which a nonvolatile solute has been added. Notice that instead of achieving an almost flat segment as in the case of pure solvent, the cooling curves for solutions often tend to show a more noticeable slope. The freezing point for the solution may be determined graphically by extrapolating the cooling curves as shown in the figure below. The point where the curves intersect is the freezing point for the solution.



Another approach that may be used in determining the freezing point of a solution involves overlaying trend lines on certain parts of the data and calculating least-square linear curves. This is shown in the figure below for a solution (solvent + solute) that exhibits supercooling. The first graph shows the plot of the time-temperature data without any trend lines



Two trend lines have been added to the second graph. The first trend line (in black) is obtained using the linear regression feature of Excel to generate the best fitting straight line for the data between Points A and B. The second trend line (in orange) is obtained the same way for the data between points C and D.



Equations for both lines are linear and of the form y = mx + b or T = mt + b where T = Temperature, t = time in seconds and m = slope of line. The intersection of these lines represents the freezing point. Thus by solving the equations simultaneously one may determine mathematically the freezing point of the solution.