The Effect of Concentration of Ions on Boiling Point

I. Research Question

What effect does varying the concentration of ions in a solution have on its boiling point?

II. Introduction

Have you ever thought about what really happens when someone puts sodium chloride on ice; that is, what happens on a molecular level? Ever since I realized what was causing the phenomenon in which the ice melts more quickly, I have been curious: does the same effect happen with the boiling point of water?

III. Background Information

The boiling point of a substance is the temperature at which its vapor pressure is equal to the atmospheric pressure (or, the pressure around it). A substance in a liquid state has a vapor pressure that is lower than the atmospheric pressure. As temperature increases, so does vapor pressure, because vapor pressure is simply based on the kinetic energy of the molecules[1]. This is the reason why a liquid must be heated up for it to reach its boiling point.

As the strength of the intermolecular forces in a liquid increases, the vapor pressure decreases. This is because the particles in the liquid have a stronger attraction to each other; the pressure outward from the solution—the vapor pressure—is higher.

If the intermolecular forces are weaker, the vapor pressure is lower, and therefore, the boiling point is lower. The inverse is also true.

When an ionic compound like NaCl is dissolved in a solvent like H_2O, the ions, Na^+ and Cl^-, dissociate. The O^{2-} anion from the H_2O is attracted to the Na+ cation, and the H^+ cation is attracted to the Cl^- anion. This type of intermolecular force, ion—Dipole, causes the solution to have a lower vapor pressure because molecules of

an increased attraction between ions and molecules—resulting in a higher boiling point. So, what happens as you increase the concentration of the solute?

IV. Variables

Independent	1. Solute	- For comprehensiveness, 3 solutes were tested: NaCl, $CaCl_2$, and $CuSO_4$.
	2. Concentration	- For each solute, 3 different concentrations were tested.
Dependent	1. Boiling Point	- Measure using a Vernier digital temperature probe
Controlled	1. Solvent	- 100mL H_2O
	2. Atmospheric Pressure	- 0.99atm pressure - 91m elevation - 23°C temperature

The main independent variable is the concentration. The solutes NaCl, $CaCl_2$, and $CuSO_4$ were tested with various concentrations in order to obtain more accurate and comprehensive data. The concentrations of each can be found in Table 1.

The solvent is 100mL of H_2O, and the atmospheric pressure is a constant 0.99atm (at 23°C and 91m elevation). The same experiment can be performed at different elevations and temperatures (and therefore, atmospheric pressures), however, it is important that the atmospheric pressure remains constant throughout the experiment.

V. Materials

To reproduce this experiment, the following materials are required.
- 100mL solution of each:
    - NaCl: 0.50M, 0.75M, 1.00M
    - $CaCl_2$: 0.20M, 0.35M, 0.50M
    - $CuSO_4$: 0.10M, 0.25M, 0.50M
- Clamp stand and a universal clamp
- Vernier digital temperature probe

- Adjustable heating pad

- 150mL glass beaker and beaker tongs

VI. Safety

- Always wear appropriate protective gear such as safety goggles and an apron.

- Never touch a beaker that is on, or has recently been removed from, the heating pad.

- Make sure the area you are working in is clear of flammables, and ensure that nothing is at risk of melting on the heating pad.

- Do not ingest or inhale any chemicals or solutions involved in this experiment.

- $CaCl_2$ (calcium chloride):

    – Considered a mild irritant by the CLEAPPS[2]

- $CuSO_4$ (copper sulfate):

    – Considered an irritant by the CLEAPPS[3]

    - Care must be taken to ensure that this compound does not enter the environment. Dispose of it accordingly.

- In case of a chemical spill:

    - Powder: Evacuate the area until the particles settle. Then moisten the area of the spill with water and wipe or sweep it up.

    - Liquid: If the solution comes in contact with skin, rinse off the affected areas. Wipe the area where the solution spilled.

VI. Procedures

A. Preparation:

    1. Attach the universal clamp to the clamp stand.

    2. Make the universal clamp hold the Vernier digital temperature probe, with the metal sensor end facing down. Wrap the temperature probe's cable around the clamp stand to make sure it does not touch the heating pad.

3. Move the clamp stand next to the heating pad in such a way that the Vernier temperature probe is directly over the center of the heating pad.

4. Turn the heating pad on.

Figure 1: Setup of Boiling Point Measurement
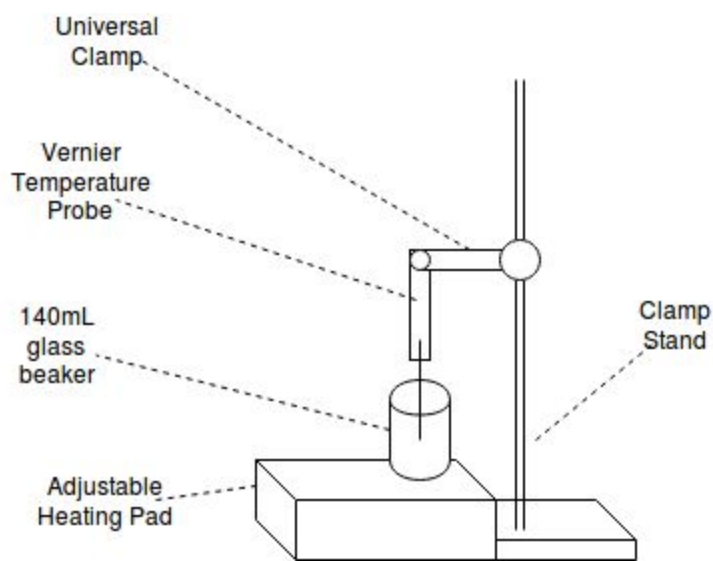
B. Repeat the following process for each solute:

1. Pour 100 mL of the solution to be tested into the 140 mL glass beaker.

2. Place the beaker on the heating pad and move the Vernier digital temperature probe into the solution.

3. Begin recording temperature data.

4. Keep the beaker on the heating pad until the solution appears to be boiling and the temperature experiences almost no change (less than 1 °C) in at least 3 minutes.

5. Stop recording temperature data, save it, and remove the beaker from the heating pad using beaker tongs.

6. Dispose of the solution and clean out the beaker.

7. Repeat steps 1-6 a total of three times for good data.

8. For each concentration of the solute to be tested, repeat steps 1-7.

VII. Data Collection

Figure 2: Average Boiling Points

	NaCl			CaCl$_2$			CuSO$_4$		
					Solutes				
Molarity (±0.01 M)	0.50	0.75	1.00	0.20	0.35	0.50	0.10	0.25	0.50
Trials (±0.1 °C)	100.7	100.3	100.5	100.1	100.2	101.7	100.1	100.4	100.4
	100.8	100.3	100.4	100.1	100.1	101.9	100.2	100.4	100.5
	100.8	100.1	100.5	100.1	100.3	101.8	100.1	100.3	100.4
Average (±0.1 °C)	100.8	101.2	101.5	100.1	100.2	101.8	100.1	100.4	100.4

Qualitative Observations:

- The amount of time to reach boiling point was around the same for all of the solutes, at about four minutes.

VIII. Data Processing

Figure 3: Uncertainty of Averages

$$U_a = \frac{\Delta t}{2} = \frac{max - min}{2} = \frac{101.9°C - 101.7°C}{2} = \frac{0.2°C}{2} = 0.1 \text{ °C}$$

Calculation of Uncertainty of Averages:

The equation in *Figure 3* was used to calculate the uncertainty of the averages. The numbers in *max-min* were taken from the trials of the test with the largest Δt, which was the 0.5M CaCl$_2$ trials.

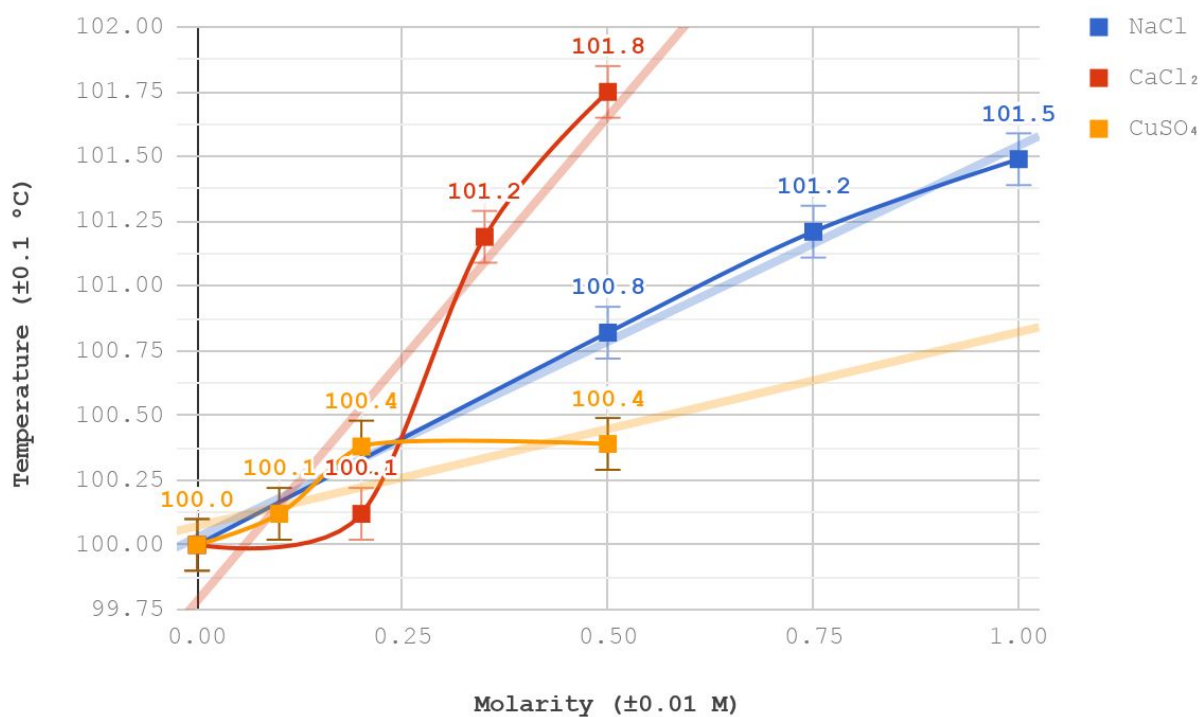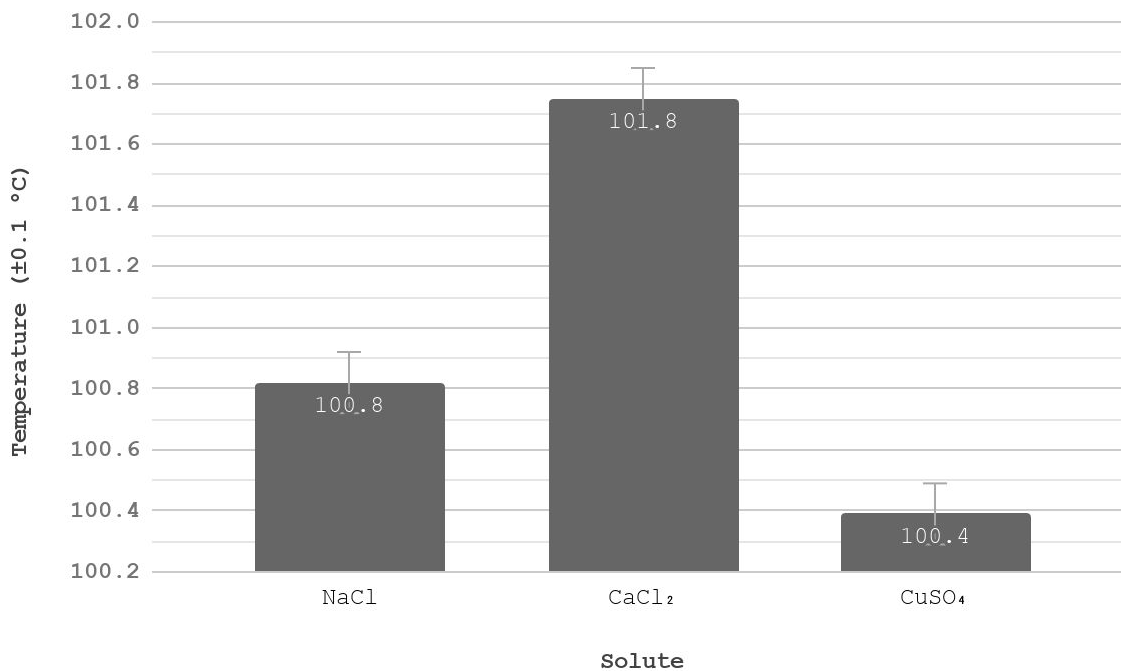Figure 4: Concentration vs. Average Boiling Points

Figure 5: Comparison of Average Boiling Point of Solutes

IX. Conclusion

Based on the data, I can conclude that the higher the concentration, the higher the boiling point. In fact, there appears to be a linear relationship between molarity and boiling point (with a different slope for each solute).

For 100mL of the 0.5 (±0.01) M solutions, calcium chloride had the highest boiling point, followed by sodium chloride and copper sulfate. Sodium chloride and copper sulfate both have relatively similar boiling points for the aforementioned concentration of solution, while calcium chloride has a relatively higher boiling point.

X. Error Analysis

The following equations are used to calculate the expected temperature change which can then be used to determine the expected boiling point. The temperature of boiling point of water at 91 meters elevation, 99.7 °C, was determined before the investigation.

1. Calculating Van't Hoff factor:

<u>Van't Hoff factor = number of dissociated ions / molecule</u>

NaCl Van't Hoff factor = Na^+ + Cl^- = 2 ions

$CaCl_2$ Van't Hoff factor = Ca^{2+} + $2(Cl^-)$ = 3 ions

$CuSO_4$ Van't Hoff factor = Cu^{2+} + SO_4^{2-} = 2 ions

2. Calculating boiling point elevation (K_b (H_2O) = $\frac{0.512\,°C}{mol}$):

$$\underline{\Delta T_b = iK_b m}$$

3. Calculating expected boiling point (T_{bw} = 99.7 °C):

$$\underline{T_{be} = T_{bw} + \Delta T_b}$$

$$T_{be} = (99.7\ °C) + i(\frac{0.512\,°C}{mol})m$$

4. Calculating percent error:

$$\%_{error} = |\frac{\#_{experimental} - \#_{theoretical}}{\#_{theoretical}}| \times 100$$

Figure 6: ΔT_b to Percent Error

Molarity (±0.01 M)	Solute	Temperature		Percent Error
		Expected (±0.1 °C)	Actual (±0.1 °C)	

0.50	NaCl	100.2	100.8	0.6%
0.75		100.2	101.2	0.7%
1.00		100.7	101.5	0.8%
0.20	CaCl$_2$	100.0	100.1	0.1%
0.35		100.2	100.2	0.04%
0.50		100.5	101.8	1.%
0.10	CuSO$_4$	99.8	100.1	0.3%
0.20		99.9	100.4	0.5%
0.50		100.2	100.4	0.2%

Admittedly, the percent error for each test noted in *Figure 6* is not as low as I would have liked. There are multiple factors that contributed to the inaccuracies that will be noted later on in this paper.

Despite the high percent error rate, the trend in the data which can be used to answer the research question still remains.

It appears as though the results for 0.5 (±0.01) M calcium chloride were anomalous; the percent error is abnormally higher than the rest of the results. In fact, it is larger than the next highest percent error by a factor of 1.7.

Error	Type	Effect	Solution
Every time I worked in the lab, I would have to set up the equipment again. Something about the setup, like using a new sensor, most likely caused variation.	Random	Data inconsistency	Perform tests the same day using the same setup
Due to the lack of time, I was unable to perform nearly as many tests as I would have liked.	Random	Incomplete or inaccurate data	Spend as much time in the lab as possible
An arbitrary amount of temperature probe was exposed	Systematic	Variation in temperature	Make probe be in a fixed position

to air.			
Part of the compound stuck to the walls of the measuring cup.	Systematic	Increased uncertainty	Ensure nothing remains in measuring cup

XI. Further Investigations

Given the opportunity to continue investigating, I would definitely try to reduce inaccuracy. As indicated in the Error Analysis section, there were a lot of inconsistencies with the data, and as a result, it was more difficult to reasonably draw a conclusion. Many steps could have been taken to mitigate this, and given more time for testing, I would have cut down on the possibility of error.

Besides normalizing the data, other aspects that affect the boiling point would be tested, such as the radius of the solvent's ions, and the atmospheric pressure.

In addition to this, the amount of time it would take to reach boiling point for all independent variables would be measured and examined for trends.

XII. References

1: https://www.chem.purdue.edu/gchelp/liquids/vpress.html

2: http://science.cleapss.org.uk/resource/SSS036-Magnesium-and-calcium-salts.pdf

3: http://science.cleapss.org.uk/resource/SSS040-Copper-and-its-compounds.pdf