2849 words

Salinity in bodies of water and specific heat capacity

Research Question: What is the effect of sodium chloride solution concentration (moldm-^{3}) upon the specific heat capacity of the solution (Jg^{-1} ^{o}C^{-1})?

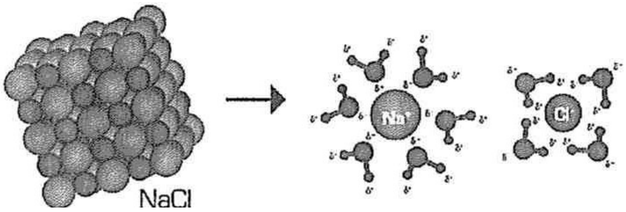
Background

Above 0 K, all particles in matter have vibrational and kinetic energy [1] When heat is applied, the intermolecular forces in matter will weaken and its particles will vibrate faster, causing an increase in temperature [2]The stronger the intermolecular forces, the more energy will be required to weaken them, increasing particle motion and temperature [3]
Specific heat capacity is defined as the energy required to increase the temperature of 1 g of a material by 1 ^{o}C[4] .

Due to their polar H-O covalent bonds, strong hydrogen bonds will exist between opposite poles of water molecules. These will require a large amount of energy to break[5]. Thus, water will have a high specific heat capacity and its temperature will stay relatively stable as external temperature fluctuates (USGS, n.d.).
This causes the temperatures of bodies of water to remain mostly constant. Most aquatic species live in a narrow temperature range, and this is fundamental for maintenance of aquatic ecosystems [6]

Saline bodies of water have dissolved salts that affect their specific heat capacity [7]When dissolved, the ionic bonds holding ions in a strong lattice will break due to their attraction to the poles of water molecules. The electrostatic attraction between the ions and the oppositely charged pole of water molecules will cause them to be held in a rigid cage, or solvation shell, as below:

Figure 1. Dissolution of sodium chloride (Marks & Carpi, 2017)



This rigid cage restricts the motion of the dissolved ions. Added heat will further increase the kinetic energy of the water molecules in lieu of the dissolved ions. This results in a lower specific heat capacity of the solution as the same mass of solution will have greater increase in temperature [8]

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[1] (Muir, 2010).
[2] (Ophardt, 2003)
[3] (Parkinson, 2000).
[4] (Wu, 2018).
[5] (Boundless, 2019)
[6] (USGS, 2018).
[7] (Urban, 1932; USGS, 2018).
[8] (Zinck , 2015).

The salinity of bodies of water have shown changes over the past century such as through agricultural runoff, the melting of glaciers by global climate change and salt water intrusion[9]. This will have an impact on their thermal properties.

I expect an increasing NaCl concentration to cause a decreasing specific heat capacity. Thus, I also expect for the NaCl solution's change in temperature to increase with increasing salt concentration.

Independent variable: Concentration of NaCl (moldm^{-3}). I will change it by preparing solutions of different concentrations with NaCl powder (measured with an electronic scale) and distilled water in a volumetric flask. I have chosen a range of 0, 0.250, 0.500, 0.750 and 1.000 moldm^{-3} The lower value, was chosen as control, and the upper, as a more concentrated solution could not be reached due to the increasing precipitation of impurities by the common ion effect [10]. Increasing the concentration of NaCl, also increases dissolved ions, which will resist a change in kinetic energy. The water molecules will have higher kinetic energy and the same thermal energy applied will result in a greater increase in the solution's temperature causing a lower specific heat capacity.
Dependent variables: Change in temperature of 250.0 cm^3 of NaCl solution using an electric kettle. The mean change in temperature at 0 moldm^{-3} sodium chloride solution, assuming its specific heat capacity is the theoretical value, can be used to derive the added heat in joules with the specific heat capacity formula.

The NaCl solution will also be massed to calculate the heat added and then the specific heat capacity of all trials. This will help elucidate the relationship between NaCl solution concentration and the specific heat capacity of the solution. 3 repeats will be done for each concentration to create means, minimizing random error in the results.

Controlled variables

Heating time: 40s controlled with a smartphone stopwatch. Different heating times would result in different amounts of heat added.
Heating apparatus: Always used the same electric kettle. Between trials, the kettle was allowed to cool down to 20°C, monitored with a thermometer. Different electric kettle may have a slightly different wattage so, a different amount of heat will be added in the same heating time.
Source of NaCl: Obtained from the same container. Different sources may have different amounts of impurities.

Method

Materials

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[9] (Jenkins, 2009; Inside Science News Service, 2012)
[10] (Clark, 2011)

- 4 dm^3 distilled water
- 150 g sodium chloride powder
- digital thermometer (±0.1°C)
- 250 cm^3 beaker
- 250.0 cm^3 volumetric flask (±0.6 cm^3)
- digital scale (±0.01g)
- 2200 W Sunbeam Express electronic kettle
- filter funnel
- stirring rod
- Weighing paper
- plastic spoon

1. Ensure all equipment and glassware are clean by rinsing with distilled water, and drying with a paper towel.
2. Tare digital scale and record the mass of the volumetric flask.
3. Measure mass of sodium chloride powder using a plastic spoon, according to table below.

Table1. Desired NaCl concentration (mol.dm^{-3}) versus mass of NaCl powder added(±0.01 g)

Desired concentration of sodium chloride (moldm^{-3})	Mass of sodium chloride powder added (g) (±0.01 g)
0 ±0*	0.00
0.250 ±0.001	3.65
0.500 ±0.002	7.31
0.750 ±0.002	10.96
1.000 ±0.003	14.61

*All absolute errors are to one significant figure.

4. Add the mass of NaCl to volumetric flask with a funnel and fill to 250 cm^{3}graduation at eye level with distilled water. Homogenize.
5. Measure the mass of the flask and its contents with the scale.
6. Add the contents of the volumetric flask to a 250 cm^3 beaker and mix them with the rod until salt is dissolved.
7. Measure and record the temperature with the thermometer.
8. Ensure the temperature inside the empty electronic kettle is 23.0 °C. Pour contents of the 250 cm^3 beaker into the kettle using a filter funnel, keeping the thermometer in the kettle. Turn on the kettle and allow it to run for 40s.
9. After 40s, record the final temperature of the solution. Empty contents of the kettle into a sink.
10. Allow the kettle to cool until it returns to 23.0 °C.
11. Repeat (1) to (10), increasing the concentration of the solution by one increment. Repeat (11) to have a total of 3 repeats for each of the 5 concentrations of NaCl.
12. *Figure 2. Diagram of testing apparatus*

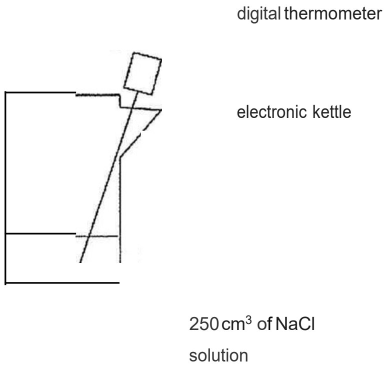

Figure 3. Example calculation of mass of NaCl powder needed for desired concentration.

$n = cV$[11]

$n = \frac{m}{M}$

$$cV = \frac{m}{M}$$

$m = McV$

Desired concentration of NaCl $c = 1.000\ \text{mol.dm}^{-3}$

$M_{NaCl} = 58.44\ \text{gmol}^{-1}$

Volume of solution $= 250.0\ \text{cm}^3 = 0.2500\ \text{dm}^3$

$$m = 1 \times 0.25 \times 58.44$$
$$= 14.61\ \text{g}$$

Safety, ethical and environmental concerns

Safety glasses must be used in the lab to protect eyes. Handle glassware with care and if glass shatters, use a brush to clear shards.
No chemicals should be consumed. Keep kettle and scale away from benchend in a dry environment.
Handle hot water and heated electric kettle with care[12].

NaCl and distilled water are not classified as hazardous chemicals and were disposed down the sink.
There are no ethical issues.

Raw data collection and processing

Table 2. NaCl concentration (moldm^{-3}) versus initial rate of temperature increase of 250.0 ±0.6 dm^3 NaCl

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[11] (IBO, 2016)

[12] (Ecosolve, 2020)

solution (slow/moderate/rapid)

Sodium chloride Concentration (mol.dm^{-3}))	Initial rate of temperature increase of 250.0 ±0.6 dm^{3} of sodium chloride solution (slow/ moderate/ rapid)		
	Trial 1	Trial 2	Trial 3
0 ±0	slow	slow	slow
0.250 ±0.001	moderate	moderate	slow
0.500 ±0.002	moderate	moderate	moderate
0.750 ±0.002	rapid	rapid	moderate
1.000 ±0.003	rapid	rapid	rapid

Table 3. NaCl concentration (moldm^{3}J versus initial and final temperature of 250.0 ±0.6 dm^{3} of solution (°C) (±0.1 °C)

Sodium chloride **concentration (mol.dm $^{-3}$)**	**Tri l 1**		**Trial 2**		**Trial 3**	
	Initial Temperature (±0 .1° C)	**Final Temperature (±0 .1° C)** (	**Initial Temperature (±0 .1° C)**	**Final Temperature (±0 .1° C)**	**Initial Temperature (±0 .1° C)** (	**Final Temperature (±0 .2° C)**
0 ±0	18.4	61.2	17.4	59.2	17.4	59.3
0.250 ±0.001	18.1	64.5	17.1	64.3	17.3	63.2
0.500 ±0.002	16.7	62.5	16.7	66.7	16.9	69.2
0.750 ±0.002	16.4	73.5	16.3	77.3	16.7	71.7
1.000 ±0.003	17.1	78.9	16.1	80.0	16.4	80.8

Figure 4. Example of sodium chloride concentration error propagation

NaCl powder mass= 14.61 ±0.01g

Percentage error for NaCl powder mass:

$\frac{0.01}{14.61}$ = 0.00068446…

= 0.0684…%

Water volume = 250.0 ±0.6 dm^{3}

$\frac{0.6}{250}$ = 0.0024

= 0.24 %

Total %error [NaCl]:
0.24% + 0.0684 % = ±0,3084 ...%

[NaCl] =1.000 mo.ldm^{-3} so

$0.3768 \ldots\% \times 1 = 0.003084 \ldots$ = ± 0.003 mol.dm-3

Example: Trial 1 of 0.750 ±0.002 moldm$^{\cdot 3}$ T_i= 16.4 ±0.1°C and T_f= 73.5 ±0.1°C.

Table 4. NaCl concentration (moldm^{-3}) versus change in temperature of 250.0 ±0.6 dm^3 of solution after 40 ±1 s of heating (±0.2 °C)

Sodium chloride concentration (mol dm^{-3})	Change in temperature of 250.0 ±0.6 dm^3 of sodium chloride solution (±0.2 °C)		
	Trial 1	Trial 2	Trial 3
0 ±0	42.8	41.8	41.9
0.250 ±0.001	46.4	47.2	45.9
0.500 ±0.002	45.8	50.0	52.3
0.750 ±0.002	57.1	61.0	55.0
1.000 ±0.003	61.8	63.9	64.4

Table 5. NaCl concentration (mol.dm^{-3}) versus mass of 250.0 ±0.6 cm^3 of solution (±0.01 g)

Sodium chloride concentration (moldm.^{3})	Mass of 250.0 ±0.6 dm^3 of sodium chloride solution (g) (±0.02 g)		
	Trial 1	Trial 2	Trial 3
0 ±0	248.66	248.59	248.50
0.250 ±0.001	250.80	250.63	250.61
0.500 ±0.002	252.86	252.80	252.90
0.750 ±0.002	255.78	255.81	255.73
1.000 ±0.003	258.60	258.51	258.49

Table 6. NaCl concentration (mol.dm^{-3}) versus specific heat capacity of solution (Jg^{-1}C^{-1})

Sodium chloride concentration (mo ld m.^{3})	Specific heat capacity of sodium chloride solution (Jg^{-1}°C^{-1})		
	Trial 1	Trial 2	Trial 3
0 ±0	4.12 ±0.07	4.22 ±0.07	4.22 ±0.07
0.250 ±0.001	3.77 ±0.06	3.71 ±0.06	3.82 ±0.06

0.500 ±0.002	3.79 ±0.06	3.47 ±0.05	3.32 ±0.05
0.750 ±0.002	3.01 ±0.04	2.81 ±0.04	3.12 ±0.05
1.000 ±0.003	2.75 ±0.04	2.66 ±0.04	2.64 ±0.04

I assumed that the solution of 0 ±0 $mol.dm^{-3}$ NaCl had the theoretical specific heat capacity of water, 4.186 $Jg^{-1}{}^{\circ}C^{-1}$:

Equation 1. Specific heat capacity formula (180 , 2012)

$$Q = mc\Delta T$$

Equation 2. Formula for mean [13]

$$\mu = \frac{\sum_{i=1}^{k} f_i x_i}{n}$$

Figure 5. Calculation of heat added and error propagation

m = average mass of 0 ±0 $moldm^{-3}$ sodium chloride solution:

$$\frac{248.66 + 248.59 + 248.50}{3} = 248.583 \text{ g}$$

Half range error:

$$\frac{258.66 - 258.50}{2} = \pm 0.08 \text{ g}$$

$$\frac{0.08}{248.5833\ldots} = \pm 0.03218\ldots\%$$

ΔT = average change in temperature of 0 ±0 $moldm^{-3}$ sodium chloride solution after 40 ±1 s of heating:

$$\frac{42.8 + 41.8 + 41.9}{3} = 42.167 \text{ °C}$$

Half range error:

$$\frac{42.8 - 41.8}{2} = \pm 0.5 \text{ °C}$$

$$\frac{0.5}{42.167} = \pm 1.1858\ldots\%$$

c = specific heat capacity of water = 4.186 $Jg^{-1}{}^{\circ}C^{-1}$

Q = heat added after 40 ±1 s of heating:

$$(248.583)(4.186)(42.167) = 43877.36\ldots \text{ J}$$

Total error:

$$\begin{aligned} &1.1858\ldots\% + 0.03218\ldots\% \\ &= \pm 1.2180\ldots\% \\ &1.2180\ldots\% \times 43877.36\ldots \\ &\qquad = 534.40569 \\ &= \pm 500 \text{ J} \end{aligned}$$

$$= 43900 \pm 500 \text{ J}$$

Figure 6. Example calculation for specific heat capacity

$$\begin{aligned} c &= \frac{Q}{m\Delta T} \\ &= \frac{43900}{(255.78)(57.1)} \\ &= 3.006\ldots \text{ Jg}^{-1}{}^{\circ}\text{C}^{-1} \\ &= 3.0 \pm 0.2 \text{ Jg}^{-1}{}^{\circ}\text{C}^{-1} \end{aligned}$$

Table 7. NaCl concentration ($mol.dm^{-3}$) versus mean specific heat capacity of solution ($Jg^{-1}{}^{\circ}C^{-1}$) and standard deviation

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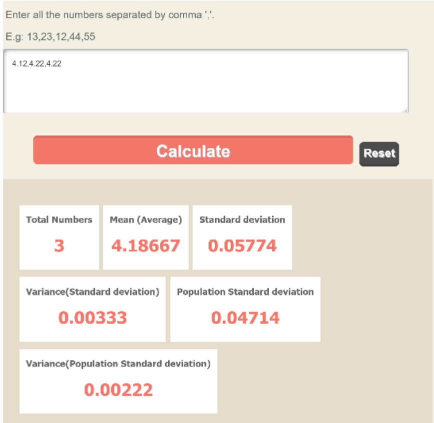
[13] (IBO, 2012)

Sodium chloride concentration (mol.dm $^{-3}$)	Mean specific heat capacity of solution (J·g^{-1} ^{0}C^{-1})	Standard deviation
0 ±0	4.19 ±0.05	0.06
0.250 ±0.001	3.77 ±0.05	0.05
0.500 ±0.002	3.5 ±0.2	0.24
0.750 ±0.002	3.0 ±0.2	0.16
1.000 ±0.003	2.68 ±0.05	0.06

The half-range error was used above for the mean specific heat capacity. The mean was evaluated using Equation 2 and the standard deviation using the following formula:

Equation 3. Formula *<u>for standard deviation</u>* (IBO, 2012)

$$\sigma = \sqrt{\frac{\sum_{i=1}^{k} f_i(x_i - \mu)^2}{n}}$$


Enter all the numbers separated by comma ','.

E.g: 13,23,12,44,55

4.12,4.22,4.22

Total Numbers 3

Mean (Average) 4.18667

Standard deviation 0.05774

Variance(Standard deviation) 0.00333

Population Standard deviation 0.04714

Variance(Population Standard deviation) 0.00222

[14]

On Graph 1, a line of best fit was formed: $c = -1.516\,C + 4.186$. Where *c* is the specific heat capacity and *C* is the concentration of sodium chloride. There was a corresponding coefficient of determination of 0.9874.

Graph 1. NaCl concentration (mol.dm^{-3}) versus mean specific heat capacity of solution (Jg^{-1} ^{o}C^{-1})

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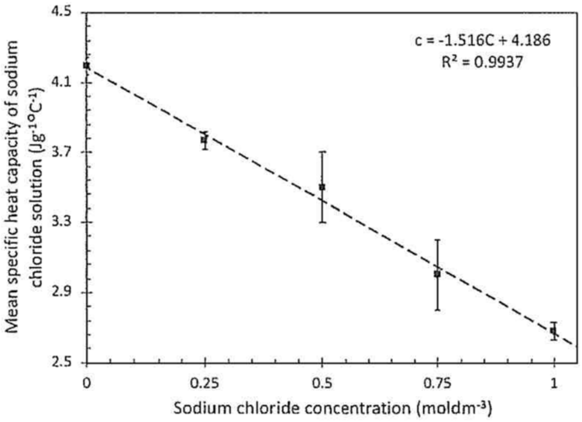
[14] https://www.easycalculation.com/statistics/standard-deviation.php



Data was further processed by calculating ρ-value from the coefficient of determination, which indicates statistical relationship for a linear data-set[15].

The null and alternative hypotheses were produced.

H_0: there is no statistically significant difference in the average specific heat capacity as the concentration of NaCl changes.

H_1: there is a statistically significant difference in the average specific heat capacity as the concentration of NaCl changes.

A threshold value of 0.05 was chosen.

A p-value of .000614 was returned by the calculator. This is much smaller than the threshold value. Hence, the alternative hypothesis, H_1, that there is a statistically significant difference in the average specific heat capacity as the concentration of NaCl changes is accepted.

Analysis and Conclusion

In Table 7, we observe a consistent decrease in the mean specific heat capacity of the solution as its concentration increases. This is also apparent in the great decrease from the minimum to maximum concentrations, from 4.19 ±0.05 to 2.68 ±0.05 $Jg^{-1o}C^{-1}$, representing a 36% decrease.

Graph 1 supports this by showing a strongly-fitting linear regression with a negative gradient of -1.516 $Jg^{-1o}C^{-1}$ $(mol.dm^{-3})^{-1}$. The strong fit is supported by the coefficient of determination, 0.9937, corresponding to a high coefficient of correlation of 0.9969 with +1 being a perfect one. There is no overlap of error bars, increasing the significance of the differences between each concentration.

There is an increasing change in temperature of the solution as its concentration increases - from an average of 42.2 °C at 0 ±0 $moldm^{-3}$ to 63.4 °C at 1.000 ±0.003 $mol.dm^{-3}$ indicating a lower specific heat capacity. There is also an increasing mass of the solution -from an average of 248.6 g at 0 ±0 $mol.dm^{-3}$

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[15] This was per formed using an online calculator by Jeremy Stangroom (2020)

to 258.5 g at 1.000 ±0.003 mol.dm^{-3}. This suggests that,in the 250 cm^3 volume, a greater proportion of the particles are the heavier dissolved sodium and chloride ions, which induce heating in water molecules and a lower specific heat capacity.

The variations in the data collected, suggest random errors. For example, at 0.250 ±0.001 moldm^{-3} the records show 46.4, 47.2 and 45.9 °C. Variation was more significant in Table 4, which considers the solution's change in temperature, than in Table 5, which considers the solution's mass. There was a maximum percentage difference between any two changes in temperature at the same concentration of 13% in Table 4 (0.500 ±0.002 moldm$^{\cdot 3}$) as compared to a maximum percentage difference between masses of 0.08% (0.250 ±0.001g). We can attribute this to the greater effect of random error in the heating process and the lower magnitude of the change in temperature values.

With error bars and standard deviation, the spread of data, likely due to random error, was considered in Table 7 and in Graph 1. The error for concentration was near negligible because all values weren't visible as error bars on Graph 1, thus the mean specific heat capacity had very small errors save at 0.250 and 0.500 moldm·3• These exceptions were still minor as reflected in the low standard deviations, which are at maximum 7% of its paired average specific heat capacity value (at 0.500 ±0.002).

Two anomalies were apparent in the data collected in Table 4. Trial 1 for 0.500 ±0.002 moldm$^{\cdot 3}$ had a resulting change in temperature of 45.8 ±0.2 °C, 3.6 °C lower than the mean. Trial 2 for 0.750 ±0.002 moldm$^{\cdot 3}$ returned a change in temperature of 61.0 ±0.2 °C, 3.3 °C higher than the mean.

The calculated values for specific heat capacity, caused an increase in variation, measured by standard deviation, from 0.11 to 0.24 and from 0.08 to 0.16, respectively. Yet, the effect that these anomalies have on the mean specific heat capacity values is marginal. Removing Trial 1 for 0.500 ±0.002 moldm$^{\cdot 3}$ would result in a mean specific heat capacity of 3.4 instead of 3.5 and removing Trial 2 for 0.750 ±0.002 mol.dm·^{3} would result in a mean of 3.1 instead of 3.0.

The qualitative observations in Table 2 supports the trends presented in Graph 1 and Tables 3, 4, 5, 6 and 7.

Statistical analysis also supports the trend because the coefficient of determination of Graph 1 explains 98.74% of the variability in the data is caused by a change in the NaCl concentration. Thus, the alternative hypothesis, was accepted.

I hypothised an increasing NaCl concentration to cause a decreasing specific heat capacity and therefore, an increasing change in temperature of the solution.

To a large extent, my data and analysis supported this hypothesis. There is a negative correlation between NaCl concentration and the specific heat capacity of the solution as supported by the qualitative, raw and calculated quantitative data. The statistical analysis by the coefficient of determination and ρ-value reinforced this, showing a statistically significant difference in the average specific heat capacity as the concentration of NaCl changed.

I conclude that as NaCl solution concentration increases, the specific heat capacity of the solution decreases answering the research question. This suggests that the changing salinities of aquatic habitats via agricultural pollution and global climate change may have an impact on the thermal properties of their water and, consequently, the species that live within them.

The formed conclusion is supported by Lucy Qu's 2016 investigation into the relationship between salinity and specific heat capacity that showed a negative correlation. '[16]

Evaluation

The controlled variables were successfully controlled, minimizing their effect on results. This contributed to the low variation and errors in the raw and processed data.
The concentration of NaCl solution, was manipulated well with low, almost negligible, errors. These was at most 0.4% of a given concentration.

As a result of these low errors, there was no overlap of vertical or horizontal error bars in the calculated data, supporting the conclusion..

The selected range (0, 0.250, 0.500, 0.750 and 1.000 moldm^{-3}) was suitable in showing a relationship between the concentration of NaCl solution and its specific heat capacity as evidenced by the difference between each mean specific heat capacity value. The effect of the concentration should have considered closer range of values in terms of the context of changing salinities of aquatic habitats. However, due to the smaller difference between raw and calculated data points, the effect of the same magnitude errors would be greater. To counteract this, it would be necessary to use more precise measuring equipment, particularly a more precise digital thermometer with an error of ±0.01 °C.

I could have reduced the effect of the same magnitude errors in raw and calculated data using a wider range of values. However, this required an increase in the upper NaCl concentration value and higher concentrations induce the precipitation of impurities by the common ion effect. Thus, it would be necessary to use purer deionized water instead of distilled water and analytical NaCl.

Despite the internal temperature of the kettle being cooled to 23 °C, some residual heat on the immersion heater likely existed. As the heating process was consistent through all trials, this may have caused a systematic increase in the change in temperature of the 250 cm^3 NaCl solution after 40 s. Through the calculation of specific heat via theoretical values, any of this systematic error was negated, though its effect on the change in temperature remained. To reduce this systematic error, I could have used another heating apparatus with a removable immersion heater, allowing the heating apparatus to be cooled in a cool water bath between trials. This would have reduced any residual heat to cause a systematic increase in the change in temperature.

The absolute error of ±1 s, resulting from human reaction, came to form a 2.5% percentage error. Though minor, it increased random error and its effect on the calculated data. The human reaction error cannot be

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[16] (Qu, 2016).

minimized, however its effect via random error can be curtailed by increasing the heating time. Though, as the heating time increases, the NaCl solution will begin to boil. To prevent the boiling of the sodium chloride solution but maintain a high heating time, a lower power electric kettle or immersion heater can be used.

I used the theoretical value for the specific heat capacity of water to calculate the heat added instead of a wattage value, because I was unable to derive it due to equipment limitations. By obtaining the wattage of the kettle, the heat added can more accurately be found. This would increase the accuracy and validity of the formed conclusions. Though, being a constant through all specific heat values calculated, this likely would not have any significant effect on the formed trends.

By calculating the true heat added, heat loss to the environment must be minimized and considered in any calculations to find accurate specific heat capacity values. Heat loss can be minimized by increasing insulation, such as polystyrene, around the heating vessel. Heat loss can also be factored, if significant, into calculations by monitoring the change in air temperature around the heating vessel and, using the specific heat capacity of air, estimating the heat lost to the environment. This would provide more accurate values for the added heat.

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