(words:2769)

An investigation on dynamic viscosity of a fluid

Research Question:

How does a change in the concentration of sodium chloride (0, 0.0684, 0.137, 0.205, 0.274, 0.342, 0.4gmol^{-1}) in sodium lauryl ether sulfate affect the solution's dynamic viscosity measured by dropping a sphere into the solution and measuring the time taken for the sphere to fall 0.185m?

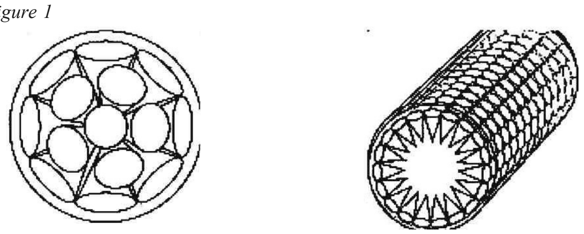
Commented [A1]: Research design, first strand: The research question is described. It includes the independent and dependent variables as well as the specifics of the system.

Introduction

Viscosity is the resistance of a fluid to a change in shape. As a fluid moves, it resists the relative motion of its adjacent parts and viscosity is therefore considered as the fluid 's internal friction (Elert, Glenn). There are two ways to measure viscosity: dynamic and kinematic and I will use the first one.

Sodium lauryl ether sulfate (SLES) is a compound commonly used in shampoos and detergents with chemical formula $CH_3(CH_2)_{11}(OCH_2CH_2)_4OSO_3Na$. It is a surfactant, which forms thick viscous liquids, and makes it easier to trap unwanted oil and grease (Sodium). When dispersed in a liquid, such as water, the anionic *SLES* surfactant molecules form particles called micelles.

Figure 1



Spherical *SLES* micelle Cylindrical *SLES* micelle after addition of NaCl

These micelles have a spherical shape and are composed of molecules with a polar head and a non-polar tail. The heads reside on the surface of the micelle because they are hydrophilic, while the hydrophobic tails point inwards. Each surfactant has a specific charge density which dictates the repulsion between micelles and how much they can pack together. A lower charge density causes the micelles to repel less and result in a thicker solution. Therefore, it is the charge density which determines how closely the micelles can pack together, affecting the liquid's viscosity.

One way to lower the charge density of the micelles is to make the solution more viscous by adding an electrolyte. The addition of NaCl introduces sodium and chloride ions to the system. These counter-ions ionically bond with the polar heads of the surfactant micelles, neutralizing their overall charge. The addition of the electrolyte causes the micelles to transform from a spherical shape to a more rod-like or cylindrical shape. As the solution is mixed, the cylindrical micelles begin to tangle up, unlike their spherical counterparts which could glide past one another, and the solution's internal friction and the viscosity of the fluid increases[1].

I predict that increasing the concentration of NaCl present in the SLES solution will lead to an increase in the dynamic viscosity of the fluid, but this will only occur up to a certain concentration of NaCl. If the concentration of NaCl is too high, the micelle head groups will be over-compressed. This results in a shift from rod-like micelles to sheet-like planar bilayer micelles that slide past each other rather than tangling up and therefore dropping the fluid's viscosity[2].

Method

Independent Variable: NaCl concentration in SLES solution (mol dm^{-3})

Masses of NaCl: 0g, 0.4g, 0.8g, 1.2g, 1.6g, 2.0g, 2.4g

To convert the grams of NaCl added to the SLES into a concentration I have used the $n=\frac{m}{M}$ and $n=\frac{c}{V}$ formulas where V is the I00cm^3 volume of SLES. This is a sample calculation for the 0.4g NaCl:

$$V = \frac{d}{t} = \frac{0.185 \pm 0.0005}{1.40 \pm 28.6\%} = \frac{0.185 \pm 0.27\%}{1.40 \pm 28.6\%} = 0.132 \text{m/s} \pm 28.9\%$$

I calculated the uncertainty by converting absolute uncertainty into percentage uncertainty, to then add the percentage uncertainties. The latter are multiplied by the final concentration to give the final absolute uncertainty.

$$n\text{NaCl: } \left(\frac{0.001}{0.400}\right)\times 100 = 0.25\%$$

$$\Rightarrow [\text{NaCl}]\text{: } 0.25\% + \left(\frac{0.0005}{0.1000}\times 100\right) = 0.75\%$$

$$\Rightarrow \text{Final: } 0.0075 \times 0.0684 = 5.13\times 10^{-4}$$

NaCl concentration = $0.0684 \pm 5.13\times 10^{-4}$ mol dm^{-3}

[1] Figure 1 shows this transformation in shape (The Institute).

[2] This phenomenon is known as a "salt curve" and experts in the field state that most surfactant solutions cannot tolerate more than a 2% concentration of NaCl (Romanowski, Perry). Otherwise, the salt's effects will be reversed and the fluid will be rendered even less viscous.

Commented [A2]: Research design, first strand: The research question includes a concise description of the relevant theory of direct relevance.

Commented [A3]: Research design, first strand: There is no official requirement for a hypothesis. If the candidate includes one, it should be addressed in the conclusion.

Commented [A4]: Data analysis, first strand: The recording and processing of data shows an appropriate consideration of uncertainties.

Commented [A5]: Data analysis, second strand: The uncertainty in time is very high. This will affect results and the candidate should have optimized this during the pilot.

Commented [A6]: Data analysis, first strand: The communication is clear and precise. The candidate shows careful consideration of significant figures. Units are correct and well reported.

Concentrations of NaCl in mol dm^{-3}: 0, 0.0684, 0.137, 0.205, 0.274, 0.342, 0.4. These are representative of a wide range of values that will allow to evaluate the various parts of the salt curve incrementally. They start with no salt as a control value and end up considering the 2% limit mentioned earlier.

Commented [A7]: Research design, second strand: The candidate justifies the range chosen for the independent variable based on cited reference. Due consideration to intervals is given.

Dependent Variable: Dynamic Viscosity of Solution

To measure the solution's dynamic viscosity (Pa ·s) I will use the falling sphere method,

timing the duration of an iron sphere's fall through 100cm^3 of the solution. For each concentration of NaCl, I will conduct 5 trials to minimize random errors.

Commented [A8]: Research design, second strand: Sufficient repetitions to answer the question properly.

For each independent variable value, I will measure the appropriate mass of NaCl using a 3-decimal place scale. This is then added to I00 cm^3 of the SLES solution and mixed in a beaker with a spoon until the mixture is homogeneous. This solution will be poured into a 100cm^{3}graduated cylinder to the 100cm^3 marking. Next, the iron sphere is held at the top of the cylinder and dropped.

Commented [A9]: Research design, third strand: The described method includes sufficient details to repeat it.

Simultaneously, a stopwatch is started. I will stop the stopwatch once the ball reaches

the bottom of the cylinder.

To retrieve the iron spheres, I will pour the solution into a drain through a sieve.

Calculation of Dynamic Viscosity:

In order to calculate the viscosity of the surfactant and salt solution in each trial I will

use Stoke's law (Brittanica):

$$v = \frac{2}{9} \times \frac{(D-d)gR^2}{\eta}$$

Rearranged to find the viscosity of the liquid, η, this gives: $\eta = \frac{2}{9} \times \frac{(D-d)gR^2}{v}$

Where: η = dynamic viscosity ($Pa \cdot s$) g = acceleration due to gravity (m/s^2)
D = density of the sphere (kg/m^3) R = radius of sphere (m)
d = density of the fluid (kg/m^3) v = terminal velocity (m/s)

The terminal velocity, v, is the maximum speed reached by a falling object when it has a constant velocity and is no longer accelerating (Cain, Fraser). In this experiment, I am assuming that it is equivalent to velocity because the SLES is quite thick and the sphere is unable to accelerate through it. Thus, the sphere has a constant speed. The equation for velocity, V, is V=$\frac{distance}{time}$ where the distance is the height of the graduated cylinder and the time is the average time taken for the sphere to fall from the top of the cylinder to the bottom. Once the dynamic viscosity values are calculated for each IV value, I will plot the data on a graph with NaCl concentration on the x-axis and respective dynamic viscosity on the y-axis.

Commented [A10]: Research design, second strand: The methodology includes assumptions made.

Control Variables

Size and Mass of Iron Sphere: Affect its velocity as it falls through the SLES solution. Since velocity is a variable in Stokes's law, this has an effect on the final dynamic viscosity.

The sphere's size and mass be kept constant by using the same iron sphere for each trial and measuring its distance using a digital caliper.

Initial and Final Heights: It is crucial to keep the drop height (when the timer starts) and the final height (when the timer ends) consistent between trials because changing these has an effect on the distance which the sphere has to travel and hence the time taken to do so. Seeing as distance is a component of velocity, which is a variable in the calculation for dynamic viscosity, this has an effect on the final result.

Initial height: Will be kept constant by just touching the bottom of the sphere with the top of the solution before dropping with tweezers.

Final height is when the sphere reaches the bottom of the graduated cylinder.

The concentration of the base SLES Solution: The surfactant concentration in the initial solution (prior to the addition of NaCl) could affect viscosity based on the number of surfactant micelles present for the NaCl ions to bond with. A higher concentration would likely increase the viscosity because there are more micelles affected by the salt concentration change. To keep this constant, I will use a solution with a 27% by volume SLES concentration.

Temperature: Has an effect on the kinetic energy of the particles within the solution.

A higher temperature leads to an increase in kinetic energy, thereby decreasing the strength of intermolecular forces because of an increase in speed and distance between molecules. By decreasing IMFs the micelles can move past each other more easily and the solution's viscosity drops. This will be kept constant by conducting all the trials in the same room.

At the start of each trial, I will measure the room temperature using a Pasco temperature probe. If it is more 2ºC than off the initial temperature measured I will ask for the heating/air conditioning system to be turned on.

Assumptions

- The acceleration due to gravity in my lab is 9.81m/s

The velocity of the sphere is constant.

Safety, Environmental, and Ethical Considerations

Safety: Must wear goggles, gloves, and a lab coat at all times because SLES is an irritant to both the eyes and skin (Bondi).

If the SLES comes into contact with skin wash with plenty of soap and water. If it comes into contact with eyes, rinse cautiously for several minutes.

Take measures to contain spills in order to avoid slip hazards.

Environmental:

When I have finished collecting data, in order to dispose of the SLES and NaCl solution, I

Commented [A11]: Research design, second strand: The candidate explains the methods used to measure and control the variables.

Commented [A12]: Research design, first strand: Clarification on specific IMFs would add value.

Commented [A13]: Research design, second strand: The methodology identifies controlled variables and the method for their control. Furthermore, the candidate justifies the relevance of their impact on results. The use of air conditioning is not wise as does not keep temperature constant.

Commented [A14]: Research design, second strand: The candidate addresses safety, and environmental issues that must be taken into account. They identify there are no ethical concerns.

will pour each solution down a foul-water drain, while diluting them with running water. [3]

Ethical: There are no ethical concerns in this investigation.

Data

Table 1: Data Table showing the time taken per trial and average time per concentration for an iron sphere to fall through the SLES solution in the graduated cylinder.

		Concentration of NaCl (mol dm^{-1} ± %)						
		0.0 ±0.5	0.0684 ±0.750	0. 137 ±0.630	0.205 ±0.580	0.274 ±0.560	0.342 ±0.550	0.411 0.540
Time taken for iron sphere to fall (s ± 0.01)	Trial 1	0.63	1.61	4.29	35.99	132.99	359.13	716.73
	Trial 2	0.46	1.21	5.25	36.92	123.00	330.78	763.64
	Trial 3	0.50	1.30	5.21	36.21	134.06	365.76	715.72
	Trial 4	0.55	1.40	5.06	35.22	126.17	345.85	644.06
	Trial 5	0.57	**1.61**	4.94	36.46	129.6 5	353.67	709.78
	Trial 6	0.50	1.89	5.17	33.58	160.27	353.28	742.90
	Trial 7	0.45	1.11	4.95	34.97	153.06	325.44	713.08
	Trial 8	0.52	1.09	5.05	36.82	129.83	335.77	733.75
	Average	0.52	1.40	4.99	35.77	136.13	346.21	717.46

Commented [A15]: **Data analysis, first strand:** The communication is clear and precise. The candidate has considered units and decimal places correctly.

Commented [A16]: **Data analysis, second strand:** Some outliers are not identified.

Density of the sphere (kg/m^3)	7870						
Mass of 100cm^3 SLES in graduated cylinder (kg ± 0.000001)	0.109403	0.106846	0.1060126	0.105692	0.104182	0.103651	0.103338
Acceleration due to gravity (m/s^2)	9.81						
The radius of the sphere (m)	0.00198 ± 0.51%						

Table 2: *Raw data table of the other variables needed to calculate dynamic viscosity*

Commented [A17]: **Data analysis, first strand:** The tables are numbered and titles are clear.

Qualitative Observations

Commented [A18]: **Data analysis, first strand:** Both quantitative and qualitative data is reported. Communication is both clear and precise.

Mixture bubbles and foams after being mixed and never fully settles.

Layer of bubbles forms at the top so that the start of the ball's drop is not the same as when it is through the surfactant.

At 2.4% the solution turns white and takes on the consistency of jello, and can be cut. Hence, no ball can fall through anymore.

Room temperature remains largely consistent. Highest temp reached over 4 days is 23.6°C, while the lowest temperature reached is 21.4 °C.

[3] (CLEAPSS).

The "0.0684 mol dm^{-3}" trial will be used as example of calculations:

$$\frac{1.61+1.21+1.30+1.40+\ 1.61+1.89+1.11+1.09}{8} = 1.40s$$

To calculate the uncertainty in the average time I had to subtract the minimum value from all eight trials from the maximum value and divide by two.

$\frac{1.89-1.09}{2}$ = 0.40s

The percentage uncertainties for each average time were measured by dividing the absolute uncertainty by the average time and multiplying by 100:

$\frac{0.40}{1.40}$ x 100 = 28.6%

I have taken measurements for the necessary variables and will use the averaged times for each concentration from the previous table.

The values I need to find are:

η = dynamic viscosity ($Pa \cdot s$)	g = acceleration due to gravity (m/s^2)
D = density of the sphere (kg/m^3)	R = radius of sphere (m)
d = density of the fluid (kg/m^3)	v = terminal velocity (m/s)

Density of the sphere (D): As the size of the iron spheres used was so small,

I will use the known value for the density of iron which is 7870kg/m^3(Engineers).

Density of the fluid (d):

The density of the solution is different at each concentration:

$$d = \frac{mass}{volume} = \frac{0.106846 \pm 0.000001 kg}{0.000100 \pm 0.0000005 m^3} = \frac{0.106846 \pm 0.000936\%}{0.000100 \pm 0.5\%} = 1070\ kg/m^3 \pm 050\% = 1070 \pm 535 kg/m^3$$

Commented [A19]: **Data analysis, third strand:** The value of density falls in the uncertainty's range.

Radius of the sphere

(R): 0.00198m ± 0.00001m = 0.00198m ± 0.51%

Terminal velocity (v):

$$V = \frac{d}{t} = \frac{0.185 \pm 0.0005}{1.40 \pm 28.6\%} = \frac{0.185 \pm 0.27\%}{1.40 \pm 28.6\%} = 0.132 m/s \pm 28.9\%$$

Table 2: Processed Data used to calculate dynamic viscosity

	NaCl concentration (mol/dm^3)						
	0	0.0684	0.137	0.205	0.274	0.342	0.4!!
Terminal velocity (m/s)	3.54	1.32	0.371	0.0517	0.0136	0.00534	0.00258
Percentage uncertainty in terminal velocity	*17.49%*	*28.9%*	*9.89%*	*4.94%*	*13.96%*	*6.09%*	*8.60%*
Density of the fluid (kg/m^3)	1090	1070	1060	1060	1040	1040	1030
Percentage uncertainty in density of fluid	*0.50%*	*0.50%*	*0.50%*	*0.50%*	*0.50%*	*0.50%*	*0.50%*

Finding the dynamic viscosity for each concentration:

$$\eta = \frac{2}{9} \times \frac{(D-d)gR^2}{v}$$

Example:

$$\eta = \frac{2}{9} \times \frac{(7870-1070)(9.81)(0.00198^2)}{1.32} = 0.0509\,Pa \cdot s$$

For the subtraction, the absolute uncertainties were added and then converted to percentage uncertainty. Meanwhile, when a value was squared its percentage uncertainty was doubled. Then, when multiplying or dividing, percentage uncertainties were added.

$$[(\frac{0\,kg/m^3 + 5.35\,kg/m^3}{7869}) \times 100] + 0 + (2 \times 0.51\%) + 28.9\%$$
$$= [0.0680\%] + 1.02\% + 28.9\% = 30.0\%$$

To convert into absolute uncertainty, I multiplied relative uncertainty by dynamic viscosity:

$$0.300 \times 0.0509 = 1.53 \times 10^{-2}\,Pa \cdot s \Rightarrow 2 \times 10^{-2}\,Pa \cdot s$$

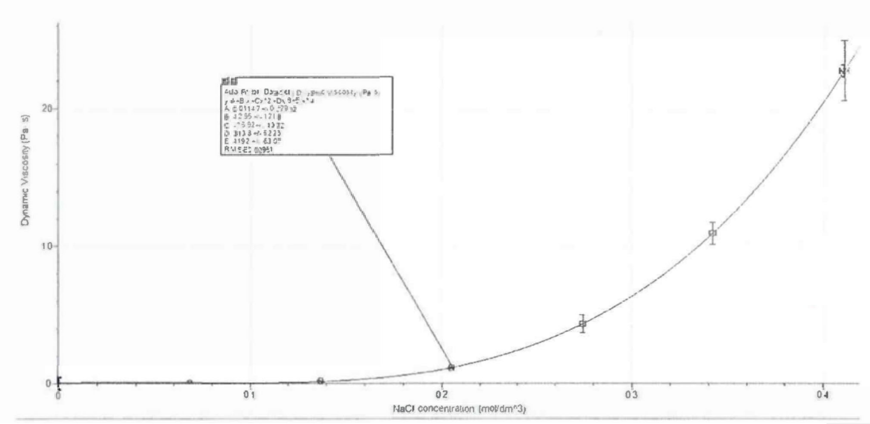
$$0.300 \times 0.0509 = 1.53 \times 10^{-2}\,Pa \cdot s \Rightarrow 2 \times 10^{-2}\,Pa \cdot s$$

Table 3: Dynamic viscosities for different salt concentrations of SLES solutions

NaCl concentration (mol/dm^3)	Dynamic Viscosity ($Pa \cdot s$)
0.000	$0.016 \pm 3 \times 10^{-1}$
0.068×10^{-4}	$0.04 \pm 2 \times 10^{-2}$
$0.1370 \pm 9 \times 10^{-4}$	$0.16 \pm 2 \times 10^{-2}$
$0.205 \pm 1 \times 10^{-3}$	$1.13 \pm 7 \times 10^{-2}$
$0.274 \pm 2 \times 10^{-3}$	$4.3 \pm 6 \times 10^{-1}$
$0.342 \pm 2 \times 10^{-3}$	$10.9 \pm 8 \times 10^{-1}$
$0.411 \pm 2 \times 10^{-3}$	22.7 ± 2

Figure 1: Graph showing the effect of NaCl concentration on a SLES solution's dynamic viscosity.

> **Commented [A20]: Data analysis, second strand:** Error bars are not mandatory. However, they can be helpful in graphical analysis. If a candidate decides to use them, they must be clear and correctly implemented.



Data Analysis

As the NaCl concentration of a sodium lauryl ether sulfate solution increases from zero to 0.411 ± 0.002 mol/dm^3, its dynamic viscosity also increases. Unlike my prediction, as the NaCl concentration increased, the dynamic viscosity increased at an increasing rate. The relationship between the two values is exponential. This is why I chose to model the data using a positive exponential trendline with equation $y=0.114e^{134}x$. The exponential nature of the trend is made clear by a relatively small difference in dynamic viscosities between the first two IVs of 0.024 Pa ·s, and the large difference between the last two IVs of 11.8 Pa ·s.

> **Commented [A21]: Conclusion, first strand:** The candidate addresses the proposed hypothesis based on results.

The final increase is over 100 times greater than the first, demonstrating that at relatively higher NaCl concentrations the addition of salt will cause a much larger change in dynamic viscosity than at lower NaCl concentrations. I chose this model because the trendline has an asymptote at y=0, which is accurate for this real-life investigation because the dynamic viscosity of a solution can never reach zero.

The R^2 value of the exponential trendline is 0.99, suggesting that the trend line models the data very precisely and that the data demonstrates a clear positive relationship between the independent and dependent variables. The line of best fit passes through all of the error bars, which suggests consistency between the trials for the independent variable value.

> **Commented [A22]: Conclusion, first strand:** The results are justified through the use of R^2.

Conclusion

Every increase in NaCl concentration led to an increase in dynamic viscosity, with the value of the change increasing each time. Although the trend was not linear as I had predicted, the positive exponential relationship still supports my hypothesis despite a varying rate of change. this trend was supported by consistent data across independent variable values and an R^2 value of 0.99, indicating accurate and precise results.

> **Commented [A23]: Conclusion, first strand:** The candidate is misinterpreting the results in this conclusion. A linear and an exponential trend are hardly the same.

I was able to demonstrate that an increase in NaCl concentration increases the dynamic viscosity of an SLES solution, following a positive exponential trend.

The experimental results are in line with the current scientific principles. Viscosity is a fluid's internal friction and is the property associated with how thick or runny a solution is (Elert). The SLES surfactant used as the solvent in the solution for this investigation was composed of spherical-shaped micelles, which could easily glide past each other having a relatively low viscosity. When the NaCl was added, its "counter-ions" bonded with the polar heads of the surfactant micelles, neutralizing their overall charge. Therefore, they were able to pack closer together to form cylindrical shapes that tangled and prohibited the micelles from moving past each other. This explains why the η values were higher at increased NaCl concentrations, seeing as the micelles were becoming increasingly tangled and the solution more viscous. However, this trend should have exhibited a curve, where at a certain point viscosity begins to decrease rather than increase. Specialists in this field predict that this should occur at a 2% concentration of salt (Romanowski). This is unexpected, but probably explained because I was testing extremely small batches of surfactant and the NaCl concentration hadn't yet reached the point where the micelles convert into planar shapes, sliding easily past each other, thus dropping the value of η.

Commented [A24]: Conclusion, second strand: The conclusion is justified through relevant comparison to the accepted scientific context.

Overall, there was a fair amount of measurement uncertainty. For certain data points in the graph the error bars were quite large. In addition, the percentage uncertainties in dynamic viscosity of 18.5% for the 0mol/dm^3 concentration, and 29.8% for the 0.137mol/dm^3 concentration demonstrate low precision. The time taken for each low viscosity trial 3 was extremely short and significant human error was present in the timing process.

Commented [A25]: Conclusion, first strand: The candidate interprets results and includes associated uncertainties. They identify high values of uncertainties.

This makes me less certain in my results, however, average viscosities for each IV value were significantly different, allowing for a clear trend and showing a high degree of accuracy in my results. My confidence is raised because I tested a sufficient number of trials and there was no overlap in error bars.

Evaluation

The inaccuracy in my methodology is indicated through the significant percentage uncertainties for each independent variable value. Some possible errors and their impacts on the results include:

Source of Error	Impact of Error	Potential Improvement
Human error in timing	Limited hand-eye coordination resulted in random errors. The times measured could have fluctuated by roughly 0.5 seconds on both the start and the end, totaling ±1.0s.	Use a photogate velocity sensor attached to either side of the cylinder (first test to check it works on opaque solutions).
The SLES and NaCl solution was never fully mixed or homogenous: the sphere droppedwould not fall straight.	There were bubbles and foam at the top and small pockets of undissolved solute throughout. This systematic error caused the spheres to fall non-uniformly. This zigzagging added distance to their fall, making their calculated velocity slower than expected. Some spheres rubbed against the cylinder's side causing extra friction and decreased velocity. This systematic error resulted in dynamic viscosity values higher than their true value. This caused imprecision because the ratio of bubbles to solution was different per trial, but there was also inaccuracy because the salt was never fully dissolved in the surfactant, meaning the micelles may not have been completely changed, thereby lessening the impact salt concentration.	I could use an electric paddle mixer, which is better than using a spoon because it is more powerful at blending and will ensure that the solute is fully dissolved. Then I will let the solution sit for least an hour so that the foam settles and the mixture is homogeneous. I could use heavier balls in a longer graduated cylinder decreasing the systematic error. .

Commented [A27]: Evaluation, second strand: Improvements should be realistic—is this instrument available? If it is, why was it not used for the experiment?

Commented [A26]: Evaluation, first strand: The error in time measurement is high, affecting the reliability of results. To the candidate's credit this is identified. The impact on the results is not stated, and the type of error is not identified. Weakness is described.

Commented [A28]: Evaluation, first strand: The candidate identifies and explains the systematic error, and states direction.

The range tested was limited. Rather than testing in increments of 0.4% NaCl, it would be better to increase by 0.2% each time to fill in the gaps and determine if the exponential trend truly fits the data.

Since I only tested up to a 2.4% (0.411 mol/dm^3) NaCl concentration the "salt curve" breaking point was never reached and I was unable to determine if this phenomenon held true for my solution. To improve, I could double the maximum concentration (0.822mol/dm^3) to observe results over a wider range of IV values.

Commented [A29]: Evaluation, second strand: The candidate considers limitations and improvements. However, considering that at 0.411 M the ball did not fall, suggesting doubling the concentration is not realistic.

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