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PHYSICS IA: HOW SALINITY AFFECTS VISCOSITY

1. INTRODUCTION

As a passionate swimmer, I know that there are many extraneous factors which affect a swimmer's speed. One of the factors is the amount of salt present in water, or in scientific terms, the salinity. I know this because I have been to many places in which I noticed that it is very difficult to swim, in particular the Dead Sea. An aqueous solution of NaCl (table salt) is known as brine. Salinities vary depending on the site of water, for example, most swimming pools do not contain salt and are rather chlorinated. On the other hand, seas and oceans both contain a lot of salt, where some have higher salinities than others. On average, the salinity of seawater is about 3.5%—that is, for every litre of seawater there are approximately 35 grams of salt dissolved in it (Andrews, 2018).

That being said, it is quite difficult to conduct an accurate experiment which directly investigates the effect of salinity on a swimmer's speed due to the presence of myriad confounding variables, as well as the miniscule time differences of the swimmer with relatively large uncertainties caused by reaction time and/or the swimmer's physical condition. Upon researching, I discovered that this topic has links to engineering physics and this is where another property becomes useful: dynamic viscosity. The dynamic viscosity of a fluid, η, is a quantity that describes the fluid's resistance to flow, and its SI unit is Pascal-seconds, Pas (Kirk, 2014). A fluid with a high viscosity will have a high resistance to flow and will require a lot of force to be able to move through it. As such, it would be logical to think that water of high viscosity will take longer to swim in than water with lower viscosity. This led me to the research question: "How does the salinity of brine affect its viscosity (Pas)?"

Viscosity can be calculated using Stokes' Law, which involves releasing a perfect sphere of known radius and density in a fluid of known density and determining the ball's terminal velocity. A ball in water will have upthrust, U, a viscous drag force, F_D, and Weight, W, all acting upon it (see **Figure 1**). For the ball to be at terminal velocity, these vertical forces must be balanced such that:

$$W = U + F_D \tag{1}$$

By substituting formulae into each of these variables and re-arranging, we can obtain an equation for viscosity as follows:

$$\eta = \frac{2gr^2(\rho - \sigma)}{9v_t}, \tag{2}$$

(Kirk, 2014)

where:

g = gravitational field strength ($\mathrm{ms^{-2}}$) = 9.81 $\mathrm{ms^{-2}}$

r = radius of sphere (m)

ρ = density of sphere ($\mathrm{kgm^{-3}}$)

σ = density of fluid ($\mathrm{kgm^{-3}}$)

v_t = terminal velocity of sphere ($\mathrm{ms^{-1}}$)

We can verify that the standard unit of viscosity is indeed Pas:

$$[\eta] = \frac{\mathrm{ms^{-2} \times m^2 \times kgm^{-3}}}{\mathrm{ms^{-1}}}$$

$$= \frac{\mathrm{kgm^0 s^{-2}}}{\mathrm{ms^{-1}}}$$

$$= \mathrm{kgm^{-1}s^{-1}}$$

$$= \mathrm{(kgm^{-1}s^{-2})s}$$

Since a pascal is a unit of pressure defined as the force ($\mathrm{kgms^{-2}}$) per unit area ($\mathrm{m^2}$):

$$1\ \mathrm{Pa} = 1\ \mathrm{kgm^{-1}s^{-2}}$$

$$\therefore [\eta] = \mathrm{Pas}$$

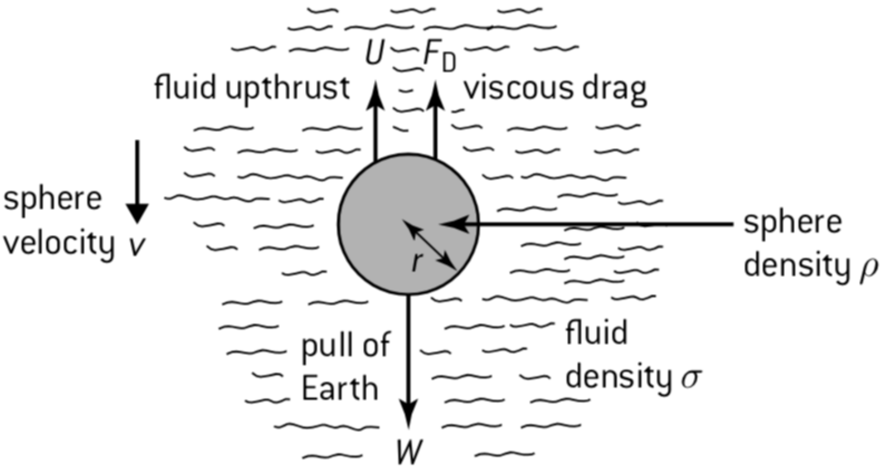

Figure 1: The properties of a perfect sphere in a fluid and the forces acting upon it.
Source: (Kirk, 2014)

2. HYPOTHESIS

Adding salt increases the mass of the fluid and consequently its density, which means that the difference in densities $(\rho - \sigma)$ would become smaller. Since this value is directly proportional to the viscosity, one could assume that there is a negative linearity between the salinity and viscosity of brine. However, this is assuming that the velocity of the sphere will not be affected by the salinity. It would make sense for the sphere to travel with a slower terminal velocity when the density of the fluid is increased, which means that a decrease in velocity results in an increase in viscosity, as they are inversely proportional, according to (2). Overall, the effect of the salinity on the viscosity should, in theory, be dependent upon both the increasing fluid density and the decreasing velocity. My intuition tells me that the latter will be the more prominent factor, meaning that an increase in the salinity should increase the viscosity of brine.

3. EXPERIMENTAL DESIGN

3.1 Variables

Independent Variable: The concentration of salt in water (gdm^{-3}). The concentration intervals are: 0, 50, 100, 150, 200, 250, 300, 350 and 400 gdm^{-3}. The highest interval cannot be higher than 400 gdm^{-3} because the maximum solubility of salt in boiling water is about 40% (Andrews, 2018). Furthermore, by having one of my intervals (0 gdm^{-3}) as a control with no salt, I was able to compare the calculated value of viscosity to the literature value of 0.89 mPas (IAPWS, 2008) at room temperature, 25℃. In order to achieve each salt concentration, an equivalent mass had to be calculated, using:

$$\text{Concentration} = \frac{\text{mass}}{\text{volume}} \qquad (3)$$

Since I used a 250ml measuring cylinder, the volume remained constant (assuming that the salt's volume is negligible), therefore the mass was figured out using (3), which resulted in increments of 12.5 grams.

Dependent Variable: The viscosity of the brine solution (Pas), which can be calculated using (2). In order to do so, the terminal velocity of the ball (ms^{-1}) was measured using a motion QED in conjunction with light gates. To increase the reliability of the results, the velocity reading was taken three times, and two balls of different radii were used to perform the calculations.

In addition to the independent and dependent variables, there are a number of other factors which might affect the viscosity, therefore need to be controlled. The table below summarizes these variables.

Table 1: Identifying and analysing control variables.

Control	Why and how it was controlled
The way in which the balls are dropped	The height of the balls from the measuring cylinder and the force applied to them before dropping could affect their velocity. I therefore dropped them from the same place—from the tip of the measuring cylinder—and with no initial force; just casually let the balls 'slip' from my hand.
Distance of separation between light gates	Since I measured the terminal velocity, the factors of time and distance had to be considered. The motion QED finds the time; however, it does not know the distance of separation between the light gates and therefore had to be adjusted manually and registered as 20cm. This was measured using a ruler and the light gates remained held in position using a clamp.
Temperature of water	Temperature is one of the factors which affects the viscosity of a fluid. Therefore, the air conditioner was set to 25℃.
Volume of water	Both the concentration and the velocity of the ball are affected if the volume of water in the measuring cylinder is changed. As a result, the volume of water for all intervals of the independent variable stayed at 250ml.

Water on the ball	Dropping the ball in water made it wet, therefore it was dried using a cloth before it was dropped again, as the added water would increase the mass of the ball, consequently affecting its velocity, and hence the calculated viscosity.
Parallax error	When filling the measuring cylinder with 250ml of water, the volume was measured at eye level to prevent parallax error—that is, the misreading caused due to the distortion when viewing from different angles.
Calibrating balance	In order to measure the mass accurately, the balance was calibrated using the weighing boat such that only the mass of the salt was measured, preventing a systematic error.

3.2 Apparatus

- Motion QED ($\pm 0.001\text{ms}^{-1}$)
- 250ml Measuring Cylinder ($\pm 2 \times 10^{-6}\text{m}^3$)
- Balance ($\pm 10^{-5}\text{kg}$)
- 30cm Ruler ($\pm 0.01\text{m}$)
- Micrometre ($\pm 10^{-5}\text{m}$)
- 500g of Table Salt
- 8 300ml Beakers
- 2 Light Gates
- 2 Steel Balls (8mm & 10mm radii)
- Cloth
- Power Pack
- Neodymium Magnet
- Stirrer
- Clamp
- Kettle
- Leads
- Weighing Boats
- Tap Water

3.3 Procedure

Firstly, eight solutions of brine were formed, ranging from 12.5g to 100g in increments of 12.5g. The salt was measured in weighing boats using a balance. In order to dissolve the salt, it was added to water in a kettle and boiled. Following that, the solutions were put in beakers and stirred using a stirrer, then were left for 24 hours to cool down to room temperature. This is shown in **Figure 2**. I proceeded by setting up the apparatus as shown in **Figure 3**. Leads were connected from the power pack to the motion QED and light gates—which were held using a clamp at a separation distance of 20cm. This was measured using a 30cm ruler. Note that the uncertainty in the distance measurement was not accounted for as there was no option to add uncertainties in the motion QED, therefore it was simply registered as exactly 20cm. Since the first interval (0 gdm^{-3}) contained no salt, that solution wasn't heated but rather tested immediately. 250ml of tap water was poured into the measuring cylinder, followed by placing the measuring cylinder between the light gates, setting the motion QED to display average velocity, and dropping the 8mm ball from the top of the measuring cylinder. After it passed

Figure 2: Brine solutions ranging from 12.5g (left) to 100g (right).

through both the light gates, the velocity was recorded. The ball was removed using the magnet, dried using the cloth, and then dropped again twice. The procedure was repeated using the larger 10mm ball, and then again for the other eight beakers of varying concentrations.

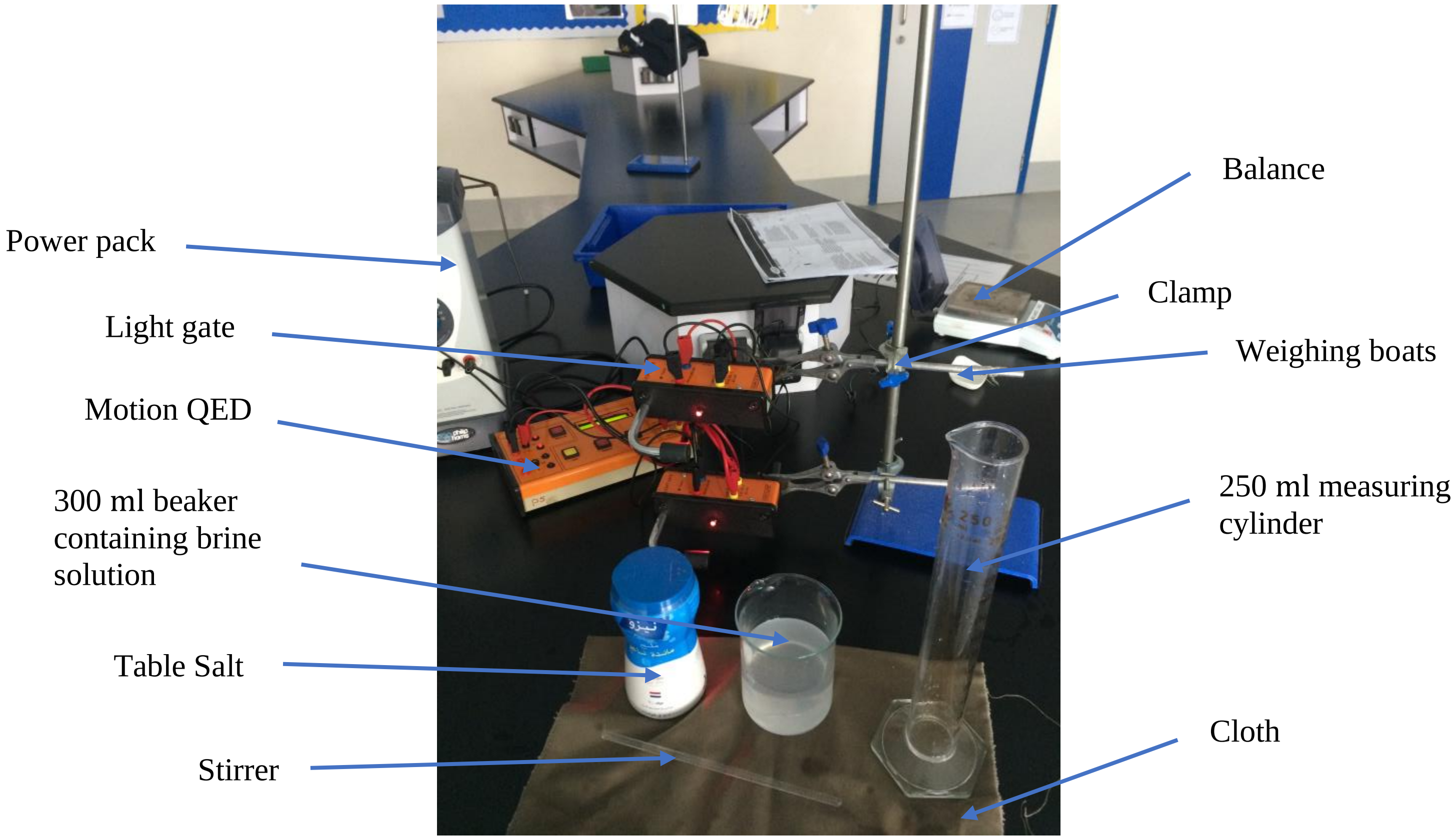

Figure 3: Annotated setup of the apparatus showing most of the equipment.

In addition to the velocity, the radius and density of the balls, as well as the density of the solutions were required to be able to calculate the viscosity. While the radii are given as 8mm and 10mm for the balls, these values are not precise and could have been rounded. As such, a micrometre was used to measure the exact radii of the balls. The volume of the sphere was then calculated using the equation:

$$V = \frac{4}{3}\pi r^3 \tag{4}$$

The balls' masses were measured using a balance, and with this information, I calculated the balls' densities using (3) (but in this case concentration is density). Similarly, the solutions' densities were calculated using (3), where the solution's mass represents the water's volume (0.25dm^3) + the salt's mass (kg). Finally, the viscosities were calculated using (2).

3.4 Safety Considerations

Care was needed when using the water-filled measuring cylinder to ensure than no water would come into contact with any of the electrical equipment as that could have damaged them. Furthermore, the neodymium magnet was very strong and therefore electronic devices had to be kept away from it. Finally, using the light gates resulted in laser light being emitted from them, so I had to be careful to not directly look at it. There were no notable environmental or ethical concerns.

4. RESULTS & NUMERICAL ANALYSIS

Table 2: A summary of the properties of the two steel balls. (3) and (4) have been used to calculate the densities and volumes respectively.

	Radius $\boldsymbol{r}$/ m $\Delta \boldsymbol{r} = \pm \mathbf{10^{-5}}$m	**Volume** $\boldsymbol{V}$/ $\mathbf{m^3}$	**Mass** $\boldsymbol{m}$/ kg $\Delta \boldsymbol{m} = \mathbf{10^{-5}}$kg	**Density** $\boldsymbol{\rho}$/ $\mathbf{kgm^{-3}}$
Small ball	0.00784	$2.02 \times 10^{-6} \pm 7.7 \times 10^{-9}$	0.01630	8080 ± 36
Large ball	0.00944	$3.52 \times 10^{-6} \pm 1.1 \times 10^{-8}$	0.02835	8050 ± 28

The values in **Table 2** have been formatted to 3 significant figures and the uncertainties to 2 significant figures, with the exception of the mass—which has been formatted to 4 significant figures—because the balance featured higher precision. We can see that the density values for the two balls are similar and this makes sense since they are made of the same material. These values are close to the accepted range for the density of steel: 7750–8050 kgm^{-3} (Wikipedia, 2019). Although the two values aren't exactly the same, the percentage difference is about 0.4%, which is negligible. All of the percentage uncertainties are miniscule, reflecting the high precision of the micrometre and the balance. The following uncertainty propagations were used to calculate the uncertainties in the volumes and densities of the balls:

$$\Delta V = 3V \frac{\Delta r}{r}$$

$$\Delta \rho = \rho \left(\frac{\Delta m}{m} + \frac{\Delta V}{V} \right)$$

Table 3: Data showing the salt concentration and the velocity of the small steel ball. Bold values are anomalies.

		Terminal Velocity $\boldsymbol{v_t}$/ $\mathbf{ms^{-1}}$ $\Delta \boldsymbol{v_t} = \pm \mathbf{0.001}$		
Concentration $\boldsymbol{c}$/ $\mathbf{gdm^{-3}}$	**Trial 1**	**Trial 2**	**Trial 3**	**Mean Velocity** $\boldsymbol{\bar{v}_t}$/ $\mathbf{ms^{-1}}$
0 ± 0.0	1.326	1.355	1.330	1.34 ± 0.015
50 ± 0.4	1.321	1.326	1.313	1.32 ± 0.0065
100 ± 0.8	**1.126**	1.285	1.297	1.29 ± 0.0060
150 ± 1.2	1.271	1.278	1.273	1.27 ± 0.0035
200 ± 1.6	1.267	1.233	1.248	1.25 ± 0.017
250 ± 2.0	1.230	1.241	**1.476**	1.24 ± 0.0055

300 ± 2.4	1.223	1.240	1.229	1.23 ± 0.0085
350 ± 2.8	1.195	1.209	1.201	1.20 ± 0.0070
400 ± 3.2	1.170	1.190	1.169	1.18 ± 0.011

Table 4: Data showing the salt concentration and the velocity of the large steel ball. Bold values are anomalies.

	Terminal velocity $v_t/\ \mathrm{ms}^{-1}$ $\Delta v_t = \pm 0.001$			
Concentration $c/\ \mathrm{gdm}^{-3}$	**Trial 1**	**Trial 2**	**Trial 3**	**Mean Velocity** $\bar{v}_t/\ \mathrm{ms}^{-1}$
0 ± 0.0	1.378	1.403	1.381	1.39 ± 0.013
50 ± 0.4	1.372	1.358	1.355	1.36 ± 0.0085
100 ± 0.8	1.346	1.350	1.350	1.35 ± 0.0020
150 ± 1.2	1.311	1.335	**0.632**	1.32 ± 0.012
200 ± 1.6	1.297	1.280	1.292	1.29 ± 0.0085
250 ± 2.0	1.258	1.276	1.270	1.27 ± 0.0090
300 ± 2.4	1.224	1.227	1.231	1.23 ± 0.0035
350 ± 2.8	1.210	1.215	1.223	1.22 ± 0.0065
400 ± 3.2	1.185	1.190	1.169	1.18 ± 0.011

By observing **Table 3** & **Table 4**, we can see that there is a negative correlation between concentration and mean velocity. Furthermore, the mean velocities of the larger ball appear to be higher on average than those of the small ball. Looking at (2), we can see that v_t is proportional to r^2, so this increase in velocity is mathematically comprehensible. The values of the mean velocity were formatted to three significant figures while their uncertainties, less precisely, have been formatted to two significant figures, as those are appropriate levels of precision given my data. Although the percentage uncertainties are quite low, with the highest being about 1.1%; the uncertainty values are close to the concordances of the three readings, which means that the reliability is not that high and could have been heavily impacted by random errors. As such, conducting five or more trials for each concentration could have potentially resulted in greater reliability. Furthermore, it could have allowed for an uncertainty calculation using standard deviation instead of half the range, which provides a much more accurate value. Some readings were identified as anomalies (shown in bold) as they were unconcordant, i.e. they did not fit within the general trend of the data. For instance, 0.632 in row 4 of **Table** 4 is significantly different from 1.335 and 1.311. As such, these anomalies were excluded from further calculations. For the following example calculations, row 2 values from **Table 4** will be used:

Uncertainty in concentration:

$$\frac{\Delta c}{c} = \frac{\Delta m}{m} + \frac{\Delta V}{V}$$

$$\therefore \Delta c = c\left(\frac{\Delta m}{m} + \frac{\Delta V}{V}\right)$$

$$\Delta c = 50\left(\frac{0.01}{12.5} + \frac{0.002}{0.250}\right)$$

$$\Delta c = \pm 0.4\underline{4}$$

$$= \pm 0.4\ \text{gdm}^{-3}\ (1\ d.p.)$$

Calculation of mean velocity:

$$\bar{v}_t = \frac{v_1+v_2+v_3}{3}$$

$$\bar{v}_t = \frac{1.372+1.358+1.355}{3}$$

$$= 1.36\underline{1}\ \text{ms}^{-1}$$

$$= 1.36\ \text{ms}^{-1}\ (3\ s.f.)$$

Uncertainty in mean velocity:

$$\Delta\bar{v}_t = \frac{v_{t\,max}-v_{t\,min}}{2}$$

$$\Delta\bar{v}_t = \frac{1.372-1.355}{2}$$

$$= \pm\ 0.0085\ \text{ms}^{-1}\ (2\ s.f.)$$

Table 5: Variation of mass & density of the brine solution with increasing salinity.

Mass $m/$ **kg** $\Delta m = \pm 0.002$	**Density** $\sigma/$ kgm^{-3}
0.2500	1000 ± 16.0
0.2625	1050 ± 17.6
0.2750	1100 ± 18.0
0.2875	1150 ± 18.7
0.3000	1200 ± 19.4
0.3125	1250 ± 20.2
0.3250	1300 ± 21.0
0.3375	1350 ± 21.8
0.3500	1400 ± 22.5

Table 6: Data showing the relationship between salt concentration and viscosity of brine solutions using two steel balls of different radii.

Concentration $c/$ gdm^{-3}	**Viscosity** $\eta/$ **Pas**	
	Small ball	**Large ball**
0 ± 0.0	0.710 ± 0.014	0.987 ± 0.017
50 ± 0.4	0.714 ± 0.011	1.00 ± 0.015
100 ± 0.8	0.719 ± 0.010	1.00 ± 0.010
150 ± 1.2	0.724 ± 0.0090	1.01 ± 0.018
200 ± 1.6	0.733 ± 0.017	1.03 ± 0.016
250 ± 2.0	0.740 ± 0.011	1.04 ± 0.017
300 ± 2.4	0.738 ± 0.013	1.07 ± 0.013
350 ± 2.8	0.750 ± 0.013	1.07 ± 0.016
400 ± 3.2	0.761 ± 0.015	1.09 ± 0.020

Table 6 suggests that the there is a positive correlation between concentration and the viscosity of the solution for both balls, which was expected; however, the viscosity values between the two balls differ significantly by about 0.3 Pas, which was not expected, as they should, theoretically, be similar. Furthermore, there seems to be a systematic error of ~10$_3$ for all the values, since we know that the true value of water's viscosity is 0.89 mPas, whereas the values obtained are significantly higher. These errors will need to be taken into consideration during further analysis. The viscosity uncertainties have been formatted to three decimal places and are relatively low, ranging from 1.0%–2.3%. As for the uncertainty calculations, using the second row for the large ball:

$$\eta = \frac{2gr^2(\rho-\sigma)}{9v_t} \qquad \therefore \eta = \frac{2\times 9.81\times(0.00944)^2\times(8050-1050)}{9\times 1.36} = 1.00\ (3\ s.f.)$$

$$\frac{\Delta\eta}{\eta} = 2\frac{\Delta r}{r} + \frac{\Delta v_t}{v_t} + \frac{\Delta(\rho-\sigma)}{\rho-\sigma} \qquad \therefore \Delta\eta = \eta\left(2\frac{\Delta r}{r} + \frac{\Delta v_t}{v_t} + \frac{\Delta\rho+\Delta\sigma}{\rho-\sigma}\right)$$

$$\Delta\eta = 1\left(2\frac{1\times10^{-5}}{9.44\times10^{-3}} + \frac{0.0085}{1.36} + \frac{26+17.6}{8050-1050}\right) = \pm 0.014\underline{5}\ \text{Pas} \qquad \therefore \Delta\eta = \pm 0.015\ \text{Pas}\ (2\ s.f.)$$

5. GRAPHICAL ANALYSIS

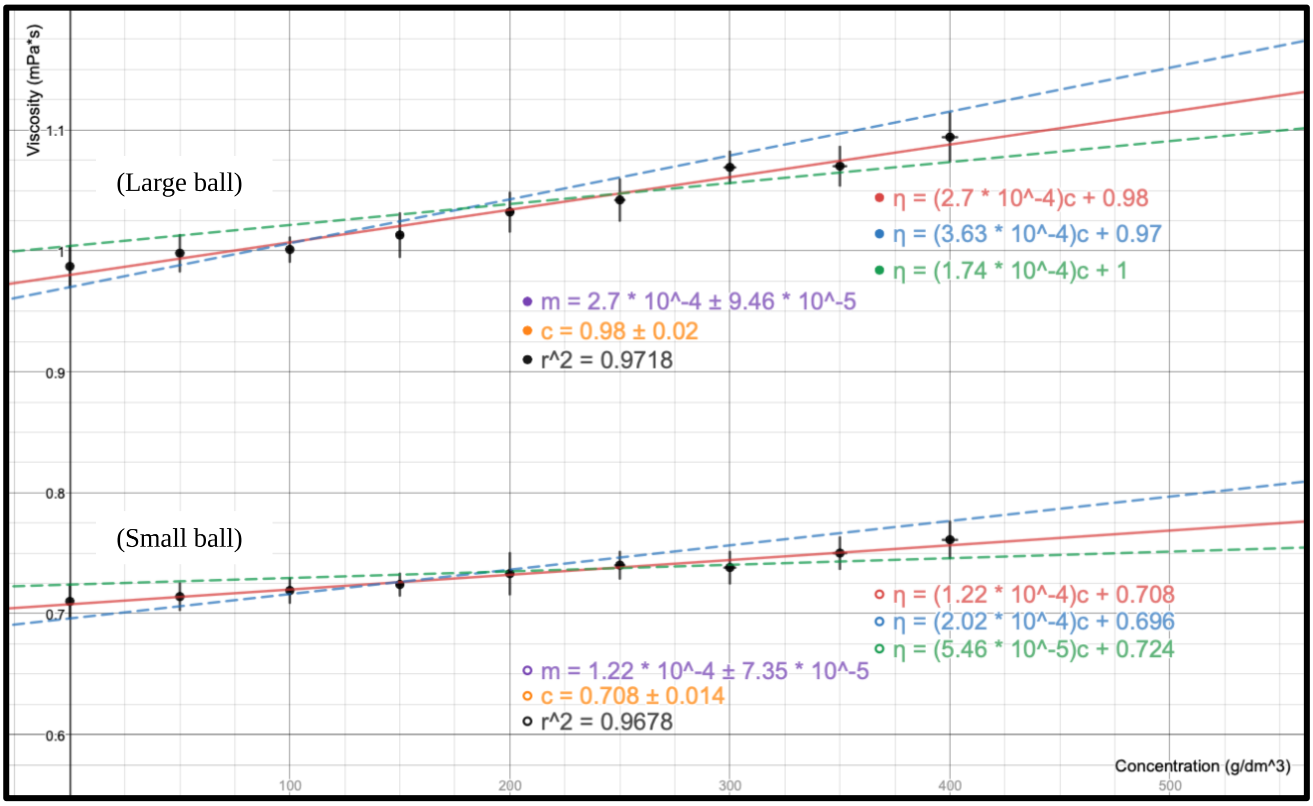

Figure 4: A graph (created using Desmos) showing a linear relationship between salt concentration, c, and viscosity, η, using a small steel ball and a larger one. The lines of best fit ($y = mx + c$) are indicated with the red line, while the blue and green lines represent the maximum and minimum slopes respectively. The equations, gradients, η intercepts and r^2 values are given.

From the previous section we know that there was a large systematic error in the viscosity values, therefore all the data points have been translated 10^3 units down (although the values are the same, the units changed to mPas, which represents the shift). We can see that the best fit line passes through all the data points, and that there is a very strong relationship for both balls as the r^2 values are 0.9678 and 0.9718 for the small and large balls respectively, reflecting the high precision of the data. The R-squared test assesses the degree of correlation between two variables. A value of 1 shows a perfect fit between the trendline and the data, i.e. a strong linear relationship, whereas a value of 0 shows no statistical relationship between the line and the data. In spite of the high r^2 values, the accuracy of the data seems to be lacking as the η-intercepts for both balls are different from what is to be expected. The viscosity of saltless water at room temperature is 0.89 mPas, however the values obtained from both balls are different from this; although the large ball's value (0.987 mPas) is closer to the true value than the small ball's value (0.71 mPas). Interestingly, the large ball's gradient is more than double that of the small ball's, which is strange since the viscosity should technically be increasing at the same rate with respect to concentration, regardless of the ball used. Although the individual error bars seem to be small and relatively insignificant (particularly the horizontal ones for the concentrations), there are whopping uncertainties in the gradients, at 35% for the large ball and 60% for the small ball; an aspect which hinders the strength of the linear relationships. On the other hand, the uncertainties in the intercepts are significantly lower at about 2%.

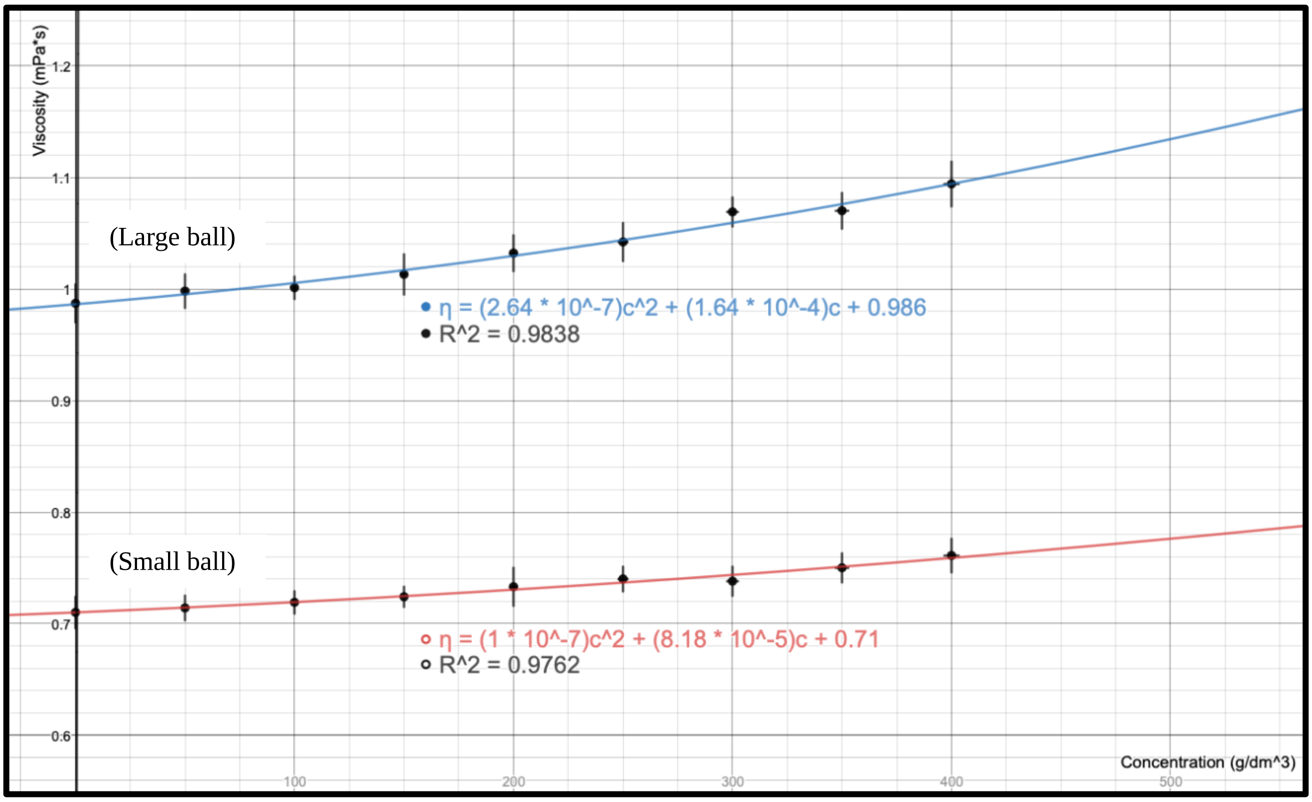

Figure 5: A graph (created using Desmos) showing a quadratic relationship between salt concentration, c, and viscosity, η, using a small steel ball (red) and a larger one (blue). The equations and the r_2 values are given.

In addition to the linear graph, quadratic models have been plotted. Similarly, the models pass through all the data points. At first glance, the quadratic models seem to fit better than the linear ones, due to the slightly higher r_2 values, however this is a point of discussion.

6. CONCLUSION

In response to my research question "How does the salinity of brine affect its viscosity (Pas)?", the data obtained seems to support my hypothesis that increasing salinity increases viscosity; a positive correlation. Two different models have been found, linear and quadratic. Although the statistical analyses have showed that the quadratic model is better than the linear model, it is important to be critical of the fact that quadratic models are contextually unrealistic, as they grow rapidly. While the model may pass through all of the current data very well, it may not be generalisable for higher values. In other words, at a much higher salt concentration than my highest salinity interval, $400\ \text{gdm}^{-3}$, the viscosity value according to the model—when extrapolated—would be extremely high due to the increasing rate of change of a quadratic function, which is impractical. In contrast, the linear model has a constant rate of change, therefore higher values of viscosity are predictable and more likely to be accurate. Furthermore, a linear relationship is generally better since it mathematically makes sense and is more commonly found within many physical phenomena. As such, the most suitable relationship between the salinity (c) and viscosity (η), according to this investigation, can be quoted as:

$$\eta = 0.000122c + 0.0000946 \tag{5}$$

This is the equation of the line given in **Figure 4** using the large ball.

The findings of my investigation can be linked back to what sparked my interest in investigating this topic. Since salinity and viscosity are directly proportional, it makes sense that it would be harder to swim in more salty areas such as the Dead Sea, as more force is required to "push through" the water. This also means that it would take longer to swim in salty water than in swimming pools, assuming that chlorine has no effect on viscosity, however this could be a topic for further investigation. As such, an implication could be that swimmers are likely to perform better in less salty water.

7. EVALUATION

Although I took into consideration the extraneous variables which could affect my investigation, there were a few assumptions made and limitations to the experiment which could have hindered the validity of my results. According to Stokes' law, the velocity measured should be the ball's terminal velocity. Since I measured the average velocity between two points, it is uncertain whether or not this represented the terminal velocity. This is more applicable to the small ball than the large one, because if we look at (2), we can see that for a fluid of constant viscosity, a ball of larger radius would have a lower terminal velocity that is more achievable experimentally. This maybe explains why the small ball's gradient percentage uncertainty is almost double the large ball's. These uncertainties were relatively high and could have potentially hindered the precision of my overall results. It could have perhaps been due to the number of calculations involved in calculating the viscosity using the measured terminal velocity and other variables, all of which possess relatively few uncertainties, but cumulatively led to a somewhat large uncertainty.

It was also strange that the two balls had different rates of change, i.e. gradients. In order to resolve the issue of varying gradients, it could be beneficial to conduct further conditions where different sized balls are used and then comparing the gradients, which could help in determining a more accurate and valid value for the rate of change. That being said, the gradient of the graphs does not represent any meaningful physical quantity but rather simply shows the rate of change. As such, the value of the gradient should not be a significant issue as it does not weaken the idea that there is a positive linear relationship.

Additionally, the results lacked accuracy as they were significantly different from the true values as aforementioned. The reason as to why the viscosity value for water was off by about 10_3 is perhaps due to the balls' terminal velocity values being incorrect, as this variable is the most likely to have been altered due to the experimental design. The separation between the light gates was 20cm, which means that the balls perhaps did not have enough time to reach their terminal velocity. This is demonstrated in the calculations below, which determine the 'true' terminal velocity value which corresponds to a known literature value of the viscosity. Rearranging (2) for the terminal velocity:

$$v_t = \frac{2gr^2(\rho - \sigma)}{9\eta}$$

Substituting in values for the variables and for the viscosity of saltless water:

$$v_t = \frac{2 \times 9.81 \times 0.00944^2 (8050 - 1000)}{9 \times 0.00089}$$
$$\approx 1540 \text{ ms}^{-1} \ (3\ s.f.)$$

As we can see, this value is extremely and unexpectedly large and is significantly different from the velocity measured, 1.387ms^{-1} (see **Table 4**), differing by an order of magnitude of 10^3. This makes sense as it explains the large systematic errors found in **Figure 4**. Since water is not a very viscous fluid, the short distance between the light gates was not enough to achieve this calculated terminal velocity. Using a larger measuring cylinder (e.g. 500 ml) could help in mitigating this systematic error as it would allow for a greater separation distance thus giving the balls more time to reach a higher velocity closer to the terminal velocity. Moreover, a larger measuring cylinder would have decreased the proximity between the balls and the walls thus reducing the impact on the velocity being altered. Although, using a larger measuring cylinder would have required more water and consequently more salt in order to achieve the same concentrations.

Despite these systematic and random errors which hindered the accuracy and precision of the results, a strong linear correlation is evident, suggesting that viscosity is directly proportional to salinity.

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