Physics – Higher Level

Extended Essay

Research Question:

“To what extent does the salt-water ratio (0, 4, 8, 12, 16, 20%) affect the terminal velocity of a plastic ball traveling through water?”

Word Count: 3871

1. INTRODUCTION

1.1 Research Question

"To what extent does the salt-water ratio (0, 4, 8, 12, 16, 20 %) affect the terminal velocity (ms^{-1}) of a plastic ball traveling through water?"

1.2 Introduction

Velocity is the most fundamental part of Physics as it encompasses each major part of Physics and is used in most formulas for calculations. A branch of physics which is heavily based around the concept of velocity and friction is aerodynamics. Aerodynamics is reliant on objects behaving around other moving objects and reducing friction they cause each other. This friction known as drag force is what limits air vehicles such as helicopters, drones, planes, etc. from moving faster in the air. This limit is known as the terminal velocity and many objects without extra energy cannot go past this speed. For example, the reason why, in skydiving, people don't accelerate forever and plummet down to the ground is due to it. Many things we see are affected by this force, however due to our air not having significant changes in temperature we don't get to see how temperature affects the terminal velocity of objects…

1.3 Aim & Rationale

Ever since I was a child, I have been deeply fond of and curious of planes and other crafts that travel through the air such as rockets. As time went on, my curiosity remained at the same level as I focused more and more on my studies as I grew up. However, with the introduction of high school physics, which also encompassed friction, drag, and small bits of aerodynamics, the interest within me increased again as I learned more and more about the topic. Additionally, as we had to choose extended essay topics, I wondered how I could incorporate air and fluid dynamics into my extended essay. I then stumbled upon how scientists design specific tools and drones to best fit their environment such as objects having larger wings in air and smaller ones in water for better movement. The reason was due to viscosity and how it shaped how scientific technologies were designed. So, for my research question I wanted to see how viscosity would change due to some factor and how this could affect the terminal velocity objects could reach. My first thought was temperature however, it was hard to see the change in viscosity in water so a change in salt concentration would make it easier to see difference in velocities.

2. BACKGROUND INFORMATION

2.1 Falling and Drag

Acceleration and Velocity

In Physics, all objects apply gravity to each other, the amplitude increases as the mass gets bigger. This is why all objects on earth get pulled to the centre of it. Due to gravity acting on objects, if they were falling, they would accelerate continuously which lets us derive this formula:

$$F = m * a$$

Where:

F, is the force of the particle,

m, is the mass of the particle,

a, is the acceleration of the particle which can be replaced with gravity which gives us:

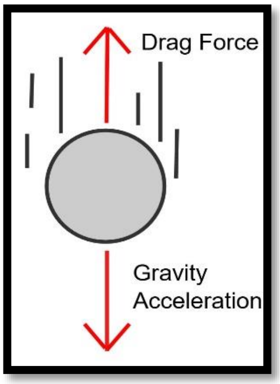
$$F = m * g$$

Terminal Velocity

This formula is widely used in physics however this does not take into consideration of all forces that act onto an object in freefall. Air consists of molecules and objects travelling through it will get slowed down due to friction. This force is calculated with this formula:

$$Drag = V * A * rho * Cd$$

Where:



V, is the velocity

A, is the surface area air particles collide with

Rho, is the air density

Cd, is the drag coefficient that changes due to shape and size of object

As you can see, as the velocity increases, so does the drag force applied on the object. With the previous formula that accelerated objects free falling, this formula shows the drag force acting opposite to the force of gravity. But as time goes on the velocity of the object is so high that the drag force is equivalent to gravity's acceleration which stops it from falling any faster. This is called terminal velocity and is calculated with this formula:

$$Fdrag = Fgravity$$

$$V * A * rho * Cd = m * g$$

2.2 Liquid Dynamics

In liquid dynamics, the process behind it is almost the same as an object falling through the air. This is due to air acting almost in the same way as liquids, flowing and moving. However, this time buoyancy is also a part of the equation. Buoyancy is the force applied to an object in a liquid to propel it up. Buoyancy force is calculated with this formula:

$$F = p * v * g$$

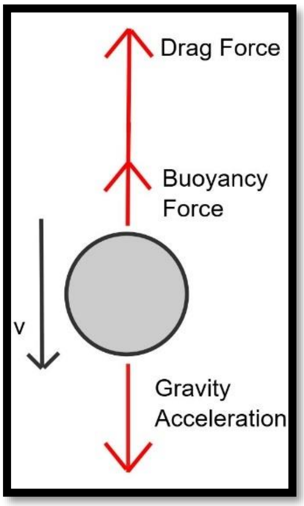
Where:

p, is the density of the fluid

v, is the volume submerged in the fluid

g, is the gravitational acceleration

If we were to investigate the free body diagram of objects falling through a liquid. We see that there are three apparent forces which are buoyancy, drag and gravity. This gives us the formula:



$$Fgravity = Fbuoyancy + Fdrag$$

However, an important thing to consider is that the drag force of liquid dynamics is different than aerodynamics which uses a different formula for calculation. This is where Stoke's Law comes which is a formula that calculates the drag force in liquids. Stoke's Law is:

$$Fdrag = 6 * \pi * \eta * r * v$$

Where:

v, is the velocity

r, is the radius of the sphere

η, is the viscosity of the liquid

These formulas can be moved to tell us the terminal velocity of an object:

$$Fbuoyancy + Fdrag = Fgravity$$

$$\text{pf} * Vp * g + 6 * \pi * \eta * r * v = mp * g$$

Where:

$P_{f,}$, is the density of fluid

V_p, is the volume of the object

M_p, is the mass of the object

Then we can change the mass of the object with the density and volume of the object which give us:

$$\text{Pf} * Vp * g + 6 * \pi * \eta * r * v = Pp * Vp * g$$

Where:

P_p, is the density of the object

Then rearranging the formula and simplify then applying the volume of a sphere we get:

$$v = \frac{(Pp - Pf) * Vp * g}{6 * \pi * \eta * r}$$

$$v = \frac{2}{9} * \frac{r^2 * (Pp - Pf) * g}{\eta}$$

Which finally gives us the formula that will be used in the experiment to calculate the terminal velocity. However, Stoke's law comes with heavy restrictions:

- The object falling must be a sphere,
- The object must have a smooth surface,
- The objects must not touch any existing wall near the liquid,
- And finally, it must exhibit laminar flow.

Additionally, commonly used formula for calculating the dynamic viscosity of salt and water mixtures is:

$$\mu = \mu water \times (1 + 0.024 \times c)$$

Where:

μ, is the viscosity of the mixture

μwater, is the viscosity of water

c, is the salt concentration in %

0.024, is the constant widely used for salinity increase at 20°C.

Laminar Flow and Reynold's Number

Laminar flow happens when the liquid around the moving object flows in a smooth manner and the flow properties in the liquid stay the same all around. For laminar flow to occur, an object must have a low Reynold's number. Reynold's number is a formula that calculates the number of turbulent forces that is happening through the motion. The formula is:

$$R = \frac{Pf * Vp * Lp}{\eta}$$

Where:

Lp, is the characteristic length of the object, which is the diameter of the sphere

Inserting the Stoke's law into the Reynold's number equation we get:

$$R = \frac{Pf * 2r}{\eta} * \frac{2}{9} * \frac{r^2 * (Pp - Pf) * g}{\eta}$$

To calculate our Reynold's number to see if it fits and exhibits the properties of laminar flow, we must first place the number into the equation:

η, is at room temperature (20°C) 1.002 mPa.s

Pf, the density of water is 1g/cm^3

Pp, the density of ball is 1.16/cm^3

g, is 9.81 m/s^2

R, the radius of the sphere is 0.30 centimetres

$$v = \frac{2}{9} * \frac{(0.30 * 10^{-2})^2 * (1160 - 998) * 9.81}{1.002 * 10^{-3}} = 3.14 m/s$$

This is the terminal velocity of the ball which is 3.14 meters per second. Then if we put this into the Reynold number formula we get:

$$R = \frac{998 * 3.14 * 0.006}{1.002 * 10^{-3}} = 18780$$

The Reynold's number is a lot higher than 2000, this tells us that the movement does not exhibit pure laminar flow and will exhibit turbulent flow. We can assume that this will slow down the ball as it travels.

The focus of this experiment is to see how salinity would affect the terminal velocity. An increase in salinity would lead to Pf (density of fluid) increasing and if depending on how salinity would affect the dynamic viscosity of water, the speed of the ball would slow down. Therefore, using a camera to measure the speed of the ball that is travelling through the water by dividing the frames it takes for the ball to fall 20cm to the camera's per second frame rate.

3. HYPOTHESIS & VARIABLES

3.1 *Variables*

Independent Variable: The salt amount in water measured in percentage (0, 4, 8, 12, 16, 20%)

The salt amount in the water will be achieved via an electronic scale that can precisely measure the weight of the salt. The right amount of salt will be weighed in and mixed with the water for each trial to satisfy each salt concentration. This way, an accurate estimation of the concentration of salt in the salt-water mixture will be done.

Dependent Variable: The time taken for the ball to fall a distance of 20cm in salt-water mixture (time taken is measured in seconds)

The data collected for the dependent variable will be done via a recording the fall of the ball and measuring the time it takes for it to displace in 20cm by slowing down the footage and measuring with the naked human eye. This might lead to an inaccuracy in data, however, by calculating the uncertainties this issue will be resolved.

Controlled Variables:

Controlled Variable	Method of Control	Reasoning
The Filming Equipment	The same camera will be used to record each trial and experiment.	Each electronic device differs from each other so, with that, other equipment could have better or worse accuracy when recording the experiment.

Temperature of Liquid	The trials will be conducted in the same environment to make sure temperature change does not affect the experiment.	A change in the temperature of the liquid will lead to a difference in viscosity therefore making the terminal velocity reached, different.
Material and Shape of the Ball	The same ball will be used for each trial and the material of the ball be non-absorbent so that it does not affect the data	Different volumes or even different texture in a spherical object may heavily change the data collected and lead to a difference in speed.
The Distance taken by the Ball	Markers and tapes will be used to make the distance the ball took is close to or exact as 20 cm.	The time taken for the trial directly affects the speed of the object during data calculation. Therefore, this variable must be controlled.

3.2 *Hypothesis*

Water is a liquid which Stoke's law can apply to. And in his law, the dynamic viscosity of the liquid is apparent and a part of the formula. Water and salt in different ratios have differing viscosities and as salt increases, the amount of friction will also increase. Thus, my hypothesis is that, as the salt amount in concentration increases, the friction will increase, thus making the terminal velocity reached by the spherical object decrease. These led me to my research question which is:

"To what extent does the salt-water ratio (0, 4, 8, 12, 16, 20 %) affect the terminal velocity (ms^{-1}) of a sphere traveling through water?"

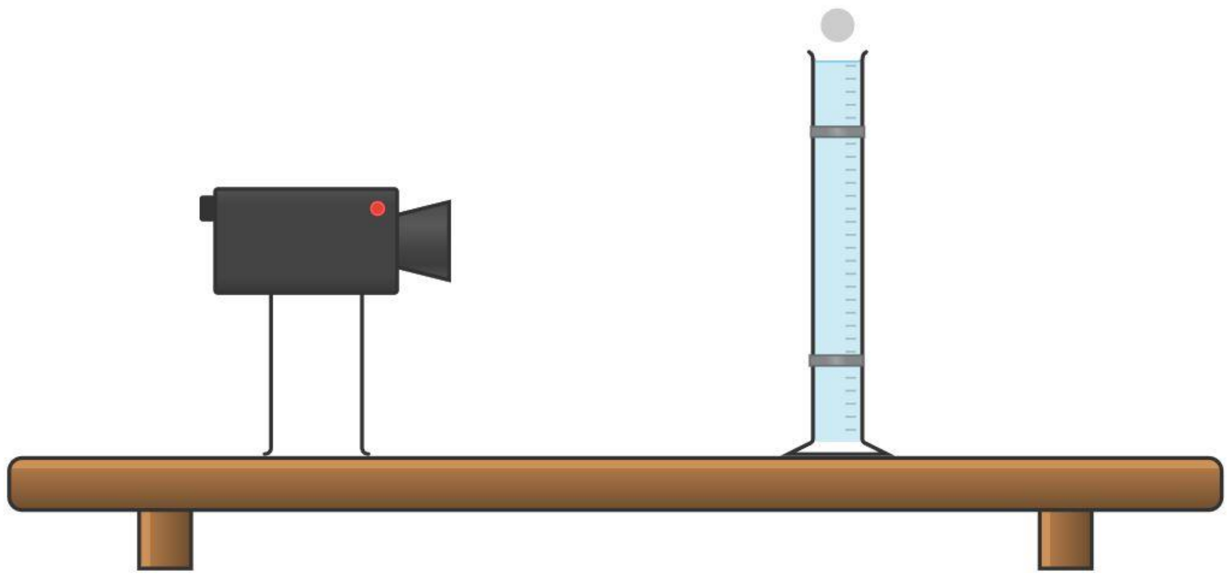
4. METHODOLOGY

4.1 *Materials*

- 1 x Glass Cylinder
- 1 x Camera (±0.016.6s)

- 1 x Plastic Ball
- Excess Water
- Excess Salt
- 1 x Electronic Scale (±0.001g)
- 1 x Ruler (±0.05cm)
- 1 x Duct Tape
- 1 x Tripod
- 1 x Stirring Rod

<u>Experimental Diagram:</u>



4.2 *Methodology*

<u>Preparing The Mixture</u>

1. First, the concentration of salt that will be used in the experiment will be decided,
2. For each ratio, these should be mixed,
   - For 0%, 1000ml of water and 0g of salt,
   - For 4%, 960ml of water and 40g of salt,
   - For 8%, 920ml of water and 80g of salt,

- For 12% 880ml of water and 120g of salt,
- For 16%, 840ml of water and 160g of salt,
- For 20%, 800ml of water and 200g of salt,

3. After stirring these mixtures with a stirring rod, it should be poured into the glass cylinder,
4. Repetition of step 1-3 is done to conduct each concentration of water.

<u>Setting Up the Experiment</u>

1. The cylinder filled with the salt-water mixture is measured with a ruler and two tape are placed apart from each other by 20cm,
2. The camera is placed onto the tripod and located in a location where the cylinder is fully visible,
3. Make sure the elevation of the camera is between the two tapes placed on the cylinder.

<u>Data Collection</u>

1. Start recording on the camera and hold the plastic ball just above the water surface,
2. Drop the ball and after it falls to the bottom of the cylinder and stop recording,
3. Remove the ball from the bottom of the cylinder,
4. Repeat steps 1-3 for each trial,
5. Viewing the video footage, measure the number of frames it takes for the ball to fall 20cm and divide the frame amount to the fps of the camera (Ex. It takes 45 frames, the camera records in 30frames per second, 45/30 which makes 1.5 seconds.)

4.3 *Risk Assessment & Justification*

Justification

The dependent variable being the time taken for the ball to take was chosen. The reason for this conclusion is other variables such as calculation the work of friction or the energy of the ball is unnecessarily complex as it can also reach the same conclusion however would take more effort during calculations and data analysis. Additionally, making the time controlled and measuring distance was also a choice but trying to control time in seconds would have led to much more inaccuracies. Thus, making time the best choice to measure the terminal velocity.

Risk and Ethical Consideration

The improper disposition of saline water would lead to a negative effect on plants and can contribute to water pollution. The salt found in the mixture can cause stunted growth in plant and could cause salinization if disposed to dirt. Salinization would result in the area being inhabitable by plants and would damage environment. If the saline water must be disposed of, it is recommended that the water should be first diluted with water so the cause would be lessened and then be disposed of through the sink. (Lattemann and Höpner)

5. PROCESSED DATA

5.1 Theoretical Data

Table 1 - Theoretical Values Using Formulas

Salt (%)	0%	4%	8%	12%	16%	20%
Water Density	998.2 kg/m^3	1001.4 kg/m^3	1004.6 kg/m^3	1007.8 kg/m^3	1011.0 kg/m^3	1014.2 kg/m^3

Mixture Viscosity	1.002 mP*s	1.098 mP*s	1.194 mP*s	1.290 mP*s	1.386 mP*s	1.482 mP*s
Velocity	3.14 m/s	2.83 m/s	2.55 m/s	2.31 m/s	2.11 m/s	1.93 m/s

5.2 Processed Data

Table 2 Average Frame per Ratio

Ratios	0%	4%	8%	12%	16%	20%
Average Frame	4.14 ± 24.1%	4.71 ± 21.2%	6.14 ± 16.3%	8 ± 12.5%	9.71 ± 10.3%	10 ± 10%

Table 3 Turning Frames into Velocities

Ratios	0%	4%	8%	12%	16%	20%
Average Velocity	2.90 ± 24.125%	2.54 ± 21.225%	1.95 ± 16.325%	1.50 ± 12.525%	1.24 ± 10.325%	1.20 ± 10.025%

Table 4 Calculating Dynamic Viscosity

Ratios	*Calculations*
Formula	$\frac{2}{9} * \frac{(0.30 * 10^{-2})^2 * (1160 - Pf) * 9.81}{\eta * 10^{-3}} = velocity$ $\frac{18 * 10^{-4} * (1160 - Pf) * 9.81}{9 \; * \eta * 10^{-3}} = velocity$ $\frac{(1160 - Pf) * 0.01962}{\eta} = velocity$
0%	$\frac{(1160 - 998.2\,) * 0.01962}{\eta} = 2.90 \; \pm \; 24.125\%$

	$$\frac{3.17}{2.90} = \eta \pm 24.125\%$$
4%	$$\frac{(1160 - 1001.4) * 0.01962}{\eta} = 2.54 \pm 21.225\%$$ $$\frac{3.11}{2.54} = \eta \pm 21.225\%$$
8%	$$\frac{(1160 - 1004.6\ ) * 0.01962}{\eta} = 1.95 \pm 16.325\%$$ $$\frac{3.05}{1.95} = \eta \pm 16.325\%$$
12%	$$\frac{(1160 - 1007.8\ ) * 0.01962}{\eta} = 1.50 \pm 12.525\%$$ $$\frac{2.99}{1.50} = \eta \pm 12.525\%$$
16%	$$\frac{(1160 - 1011.0\ ) * 0.01962}{\eta} = 1.24 \pm 10.325\%$$ $$\frac{2.92}{1.24} = \eta \pm 10.325\%$$
20%	$$\frac{(1160 - 1014.2) * 0.01962}{\eta} = 1.20 \pm 10.025\%$$ $$\frac{2.86}{1.20} = \eta \pm 10.025\%$$

Table 5 - Experimental vs Theoretical Viscosities

Ratio	**0%**	**4%**	**8%**	**12%**	**16%**	**20%**

Theoretical Viscosity	1.002 (centipoise)	1.068 (centipoise)	1.145 (centipoise)	1.25 (centipoise)	1.388 (centipoise)	1.557 (centipoise)
Experimental Viscosity	1.093 ± 24.125%	1.224 ± 21.225%	1.564 ± 16.325%	2.003 ± 12.525%	2.355 ± 10.325%	2.383 ± 10.025%

6. ANALYSIS & CONCLUSION

7. *Data Analysis*

If we were to look into to the processed data many values and trends are visible, albeit small. First factor is the relationship between the original theoretical viscosity calculated has significantly less values than the viscosity found in the experiment. Although at concentrations 0%, 4% and 8% if the errors were taken into account, it's possible the values achieved from experimentation fits within the theoretical possibility. However, as the concentration values went up, the relation between the theoretical and experimental drifted apart. The reason this could be is the salts used to form the formulas and the salt used by me. The salt I used could have had a higher density or it might have had a lower salt constant than the one widely used.

Another thing to look at is error between each concentration, due to the speed increasing as the salt concentration decreases, the number of frames used to capture the motion were less. This led to a higher uncertainty rate due to the limitations of the camera used for filming. An addition to make is the availability of better camera equipment, which can reduce the inaccuracies found within the experiment.

One large thing found is that the speed relative to the theoretical speed were smaller than expected. This is probably due to the Reynold's Number having a large quantity which made true laminar flow impossible and the turbulent forces in the liquid have made the ball slower than the theoretical. Another thing to consider is that due to the cylinder. The water molecules might have slowed near this part which essentially slowed the ball as well.

8. *Conclusion*

In summary, the effect salinity has on terminal velocity was a wonder to research on. These small looking features are nothing to scoff at as they play an enormous role and is an example on how environmental factors influence and change how physics behave around us. Adding salt to water made it denser which directly had an impact on the drag force and speed of the object traveling through fluid experienced. As the density increased, so did the buoyancy force water have on the ball. The terminal speed of the object decreased with each increasing concentration of water. Because the terminal speed was equivalent to the darg and buoyancy which directly impacted it.

Additionally, salinity changed the fluid's viscosity, which was the focus of the experiment, yet the effect of density played a larger role. Viscosity slowed the object down as it passed through the liquid accelerating and reaching the terminal speed. The increase in salinity, as it did with density, increased the dynamic viscosity of water. Terminal velocity, depending on drag force and buoyancy, decreased as the drag force applied to object increased. This shows how the salinity affects the fluid dynamics of motion while also changing its simple properties.

In the end, the relationship between terminal velocity and salinity is clear example on how environmental factors reshape the behaviour of objects. Although, the rationale was due to interest in the topic and mainly based to learn how to basics primarily work, this is still applicable in many branches which are engineering, aerospace and oceanography. Learning how salinity affected fluid dynamics gives us an idea how engineered systems are improved and changed depending on its environment.

9. EVALUATION

9.1 *Strengths*

The first strength found in the experiment was the ease of repeating the experiment. Each trial could be done in quick succession and with it more data were obtained during the experiment duration. If more trials were to be done for future data analysis, the ease of procedure is apparent and thus leading to a more reliable data.

The temperature during the conduction of the experiment was largely the same. And the liquid which was used in the trials stay the same making salt the sole and only variable that could have affected the time for the ball to fall. This makes the data clearly related to our hypothesis and rules out other factors that might have affected the data.

The concentration of salt in each mixture could be easily measured thanks to an electronic scale which makes inaccuracies less common in the data and due to its precise nature, repeating the trails and getting the more or less same data is easier via the simplicity of the preparation of the experiment.

9.2 *Weaknesses*

Weakness	Justification	Improvement
The Distance measured	The shorter the distance the higher the uncertainty would be, and this led to the experiment being more inaccurate than expected.	A cylinder with a larger height should be used or a medium in which a larger distance can be covered.
Trial amount	The number of trails has proved sufficient to prove the hypothesis yet, the small test size led to a more imprecise data.	More trials should be done, and more varying ratios should be tested.
Human Error	As best of my abilities, I have tried to precisely measure the time taken for the ball to fall however as humans, it should be considered that human error is prevalent.	Either the trail amount should be increased to a point where it is easy to see the exact human error or better equipment and tools should be used.
Camera Setup	The camera is positioned in the middle of cylinder where, the point the ball starts the 20cm distance and reaches the tip of the duct tape in the bottom may be perceived incorrectly due to the angle	A setup where two cameras which they are each lined up at the beginning and end to accurately measure the time the ball falls a distance of 20cm.

10. RAW DATA

Salinity (%)	Trial 1 (frames)	Trial 2 (frames)	Trial 3 (frames)	Trial 4 (frames)	Trial 5 (frames)	Trial 6 (frames)	Trial 7 (frames)
0%	4 (±1)	4 (±1)	5 (±1)	4 (±1)	4 (±1)	3 (±1)	5 (±1)
4%	5 (±1)	5 (±1)	5 (±1)	4 (±1)	5 (±1)	4 (±1)	5 (±1)
8%	6 (±1)	7 (±1)	5 (±1)	6 (±1)	6 (±1)	7 (±1)	6 (±1)
12%	8 (±1)	9 (±1)	8 (±1)	8 (±1)	7 (±1)	7 (±1)	9 (±1)

16%	10 (±1)	9 (±1)	9 (±1)	10 (±1)	10 (±1)	10 (±1)	10 (±1)
20%	10 (±1)	10 (±1)	11 (±1)	9 (±1)	9 (±1)	10 (±1)	11 (±1)

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