How does varying the mass of the heterogeneous catalyst, manganese (IV) dioxide (MnO_2), from 0.1g to 0.8g, with increments of 0.1g, affect the average rate of decomposition of hydrogen peroxide (H_2O_2), determined by measuring the amount of oxygen gas (O_2) produced at regular time intervals?

Introduction

Due to COVID-19, I had to clean my desk with disinfectant before sitting down in class, and with more people using disinfectants to keep themselves from getting the virus, disinfectants were seen a lot more. This made me curious as to what chemicals these disinfectants are made up of, and that is when I first came across hydrogen peroxide (H_2O_2). Interested to know about the different uses of hydrogen peroxide, I did further research and found that there are many different uses, such as helping remove bacteria from foods, clean any kind of surface, and they are part of solutions used to whiten your teeth (Joy). This research made me curious about hydrogen peroxide and inspired me to base my investigation around it.

While researching more about hydrogen peroxide, I stumbled upon something peculiar. In most photos of the chemical, and even in the lab in my school, hydrogen peroxide is generally stored in dark glass bottles, and generally not stored in warm conditions. In my school, hydrogen peroxide is stored in the fridge. The reason for this links to a chemical reaction involving hydrogen peroxide, specifically its decomposition. Hydrogen peroxide has a finite shelf life because, over time, the chemical will naturally decompose into oxygen gas and water. Thus, hydrogen peroxide is stored in glass bottles so that the bottle won't burst due to the build up of oxygen, and the dark colour helps prolong this decomposition reaction from taking place, as sunlight catalyses the reaction, and the dark colour stops sunlight from getting in. It is also not stored in warm conditions, and preferably stored in cooler conditions, because higher temperatures also catalyse the reaction ("The Decomposition of Hydrogen Peroxide: The Chemistry Blog."). This made me interested in the decomposition reaction of hydrogen peroxide, and I was curious to learn if there were any other factors that affect the kinetics of this reaction. I had to use a catalyst for this reaction as otherwise the reaction would be too slow, and this gave me the idea of changing the mass of the catalyst and seeing how, or if, this affects the kinetics of the reaction, specifically the rate of the reaction. Thus, I decided to investigate how varying the mass of the catalyst manganese (IV) dioxide affects the average rate of the decomposition of hydrogen peroxide.

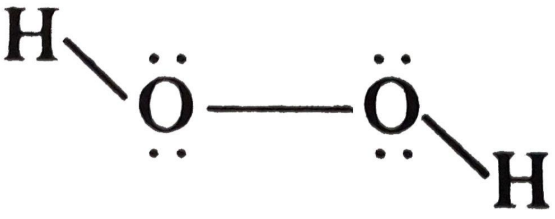
Background Information

The decomposition of hydrogen peroxide forms water and oxygen gas. The chemical equation is:

$$2H_2O_2(aq) \rightarrow 2H_2O(l) + O_2(g) \qquad (1)$$

The presence of a single oxygen-oxygen peroxide bond in hydrogen peroxide causes hydrogen peroxide to decompose as this weak and unstable bond, seen in Figure 1, eventually breaks down and releases highly reactive free radicals ("The Decomposition of Hydrogen Peroxide: The Chemistry Blog.").

Figure 1: Shows the molecular structure of hydrogen peroxide



Source: Techiescientist, 2021

The decomposition reaction of hydrogen peroxide is a disproportionation reaction. A disproportionation reaction is a redox reaction in which the same element is simultaneously oxidised and reduced. Hydrogen peroxide consists of oxygen that has an oxidation number of -1, even though, usually, oxygen has an oxidation number of -2 or 0. This property allows hydrogen peroxide to be used as both a reducing agent and an oxidising agent, and it acts as both in the decomposition reaction of hydrogen peroxide. This is because the oxygen in hydrogen peroxide is reduced to form water (the oxygen in water has an oxidation number of -2), and oxidised to form oxygen gas (which has an oxidation number of 0). Thus, since oxygen is simultaneously reduced and oxidised in the decomposition reaction, this reaction can be classified as a disproportionation reaction. The half ionic equations for the reduction and oxidation of oxygen are:

Reduction: $O^- + e^- \rightarrow O^{2-}$ (2)

Oxidation: $2O^- \rightarrow O_2 + 2e^-$ (3)

The rate of decomposition of hydrogen peroxide can be determined by measuring the amount of oxygen gas produced at regular time intervals. This is because the rate of a reaction is defined as the increase in concentration of a product per unit time and oxygen gas is a product of the decomposition reaction.

In moderate temperatures, the rate of decomposition of hydrogen peroxide is very slow. Its concentration drops by roughly 10% in a whole year, if not exposed to sunlight or warm temperatures (Stefan). Since I have to collect my results in a short amount of time, I need to increase the rate of the reaction. In order to speed up the reaction, a catalyst, specifically manganese dioxide, is used, as using a catalyst is one factor that increases the rate of a reaction.

A catalyst can be used to speed up the decomposition reaction because a catalyst is a substance that, without being chemically changed at the end of the reaction, increases the rate of a chemical reaction. It does this by decreasing the activation energy of the reaction by providing an alternate pathway. The activation energy is the minimum amount of energy which the reactant particles must possess for a collision to result in a reaction. This is one of three requirements as part of the collision theory.

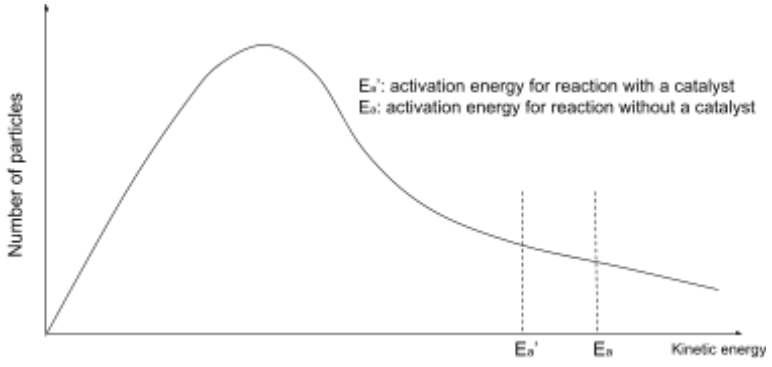
The collision theory states that, for a successful reaction to take place between two particles, three conditions must be fulfilled:

1. The particles must collide with one another
2. They must collide in the correct orientation
3. They must collide with sufficient kinetic energy (equal to or greater than the activation energy).

Successful collisions (collisions resulting with the product being formed) are known as effective collisions.

Decreasing the activation energy should result in more particles having more energy than the activation energy. This can be seen in the Maxwell-Boltzmann distribution curve for catalysed and uncatalysed reactions shown below:

Figure 2: Shows the Maxwell-Boltzmann distribution curve for catalysed and uncatalysed reactions



Source: Made by Author

As can be seen in Figure 2, the activation energy for the reaction being lowered due to the catalyst providing an alternate pathway results in more particles having the minimum energy required for a collision to be successful. This will result in more effective collisions, which increases the rate of the reaction, as the products will be formed faster. Hence, manganese dioxide is used to speed up the reaction, as it allows me to investigate the decomposition of hydrogen peroxide in a reasonable amount of time.

Manganese dioxide is a heterogeneous catalyst. A heterogeneous catalyst is a catalyst which is in a different physical state compared to the reactants. Heterogeneous catalysis is different from homogenous catalysis and involves three key steps:

1. Adsorption: Adsorption refers to something sticking to a surface. In heterogeneous catalysis, the reactant particles are adsorbed onto the surface of the catalyst at specific active sites, which is a part of the catalyst's surface and helps reactants react as they are particularly good at adsorption (Clark). In the decomposition reaction of hydrogen peroxide, the hydrogen peroxide molecules will stick to the surface of the manganese dioxide surface.
2. Reaction: The adsorption results in an interaction taking place between the reactant molecules and the surface of the catalyst, which makes them more reactive. This interaction may involve an actual reaction taking place, or may just weaken the bonds in the attached reactant molecules (Clark). In the case of the decomposition of hydrogen peroxide, the bonds in the hydrogen peroxide are weakened by the adsorption step, thus making the decomposition rate quicker. The hydrogen peroxide bonds are broken to form water and oxygen gas.
3. Desorption: After the reaction taking place, or the weakening of bonds taking place, the product molecules break away from the surface of the catalyst. This is called desorption. The product molecules leaving the surface of the catalyst also frees the active sites for a new set of reactant molecules to attach to and react with and this is how the reaction continues to take place (Clark). In the case of the decomposition of hydrogen peroxide, the water and oxygen gas breaks away from the surface of the manganese dioxide catalyst, allowing other hydrogen peroxide molecules to stick to the active sites present on the surface of the manganese dioxide catalyst.

However, since the manganese dioxide catalyst only provides an alternate pathway to the reaction with a lower activation energy, theoretically, changing the mass of the catalyst should not affect the rate of the reaction. Hence, my hypothesis for my experiment is that changing the mass of the catalyst, manganese dioxide, should not affect the average rate of decomposition of hydrogen peroxide.

Variables

Table 1: Shows the independent, dependent and controlled variables with explanations for this investigation

Variable		Explanation
Dependant	Volume of oxygen gas produced	This is used to calculate the average rate of decomposition of hydrogen peroxide
Independent	Mass of the catalyst (manganese dioxide)	The different masses used are: 0.1g, 0.2g, 0.3g, 0.4g, 0.5g, 0.6g, 0.7g, and 0.8g.
Control	Temperature of surroundings	Temperature of the laboratory was monitored and kept at 25°C using the air conditioner. If not kept constant, this would affect my experimental data, as temperature is another factor that affects the rate of a reaction. Thus, keeping the temperature constant ensured that any changes in the rate of the reaction was not due to the temperature.
	Equipment used	The same equipment was used throughout the experiment so that the uncertainties would remain constant for each data point.
	Concentration of hydrogen peroxide used	This was kept the same for each trial. If this was not kept constant, this would affect my experimental data, as concentration is a factor that affects the rate of a reaction. Thus, keeping the concentration constant ensured that any changes in the rate of the reaction was not due to the concentration.

	The same solution of hydrogen peroxide, and the same sample of manganese dioxide was used for all trials.	This was done so that if there were any small impurities present or any small variance in concentration when preparing the standard solution, these changes would be constant for all my data, and thus not affect my results as they have stayed constant for all of my trials.

Source: Made by Author

Reagents and Apparatus

Table 2: Shows equipment used including quantity and uncertainties

Name of equipment	Quantity	Uncertainty
Retort Stand	1	-
Clamp	1	-
100cm^3 Measuring cylinder	1	± 1cm^3
10cm^3 Measuring cylinder	1	± 0.2cm^3
Water trough	1	-
Rubber bung	1	-
Gas delivery tube	1	-
Test tube rack	1	-
Boiling tube	1	-
Weighing scale	1	± 0.01g
100cm^3 Beaker	1	Not needed as I do not measure anything with this beaker. Only used to store hydrogen peroxide.
Stopwatch	1	± 0.01s
Spatula	1	-
Weighing boat	2	-

Source: Made by Author

Table 3: Shows reagents used including quantity and concentration

Reagent	Quantity	Concentration
Hydrogen peroxide	$120cm^3$	$0.909091\ mol/dm^3$ (3%)
Manganese dioxide (Solid powdered form)	Total amount used: 10.8g	-
Water	Excess	-

Source: Made by Author

Risk assessment

Safety Concerns

Table 4: Shows safety concerns and control measures for compounds used.

Compound	Safety risks	Control measures
Manganese dioxide	It is harmful by inhalation or if swallowed. Many hazardous reactions occur with reducing agents or concentrated acids ("Student Safety Sheets 48 Manganese and Its Compounds.").	Wear eye protection and a lab coat. Do not inhale or swallow. Wear a mask when carrying out the experiment. Avoid contact between manganese dioxide and highly concentrated acids.
Very dilute hydrogen peroxide solution	Pressure may build up and care needs to be taken when opening a bottle. Otherwise it is not hazardous as the solution I am using is very dilute ("Student Safety Sheets 57 Hydrogen Peroxide").	Store concentrated solutions away from heat and light, in bottles with special vented caps and beware of a rapid release of pressure when opening a bottle. Store in the dark and in the fridge when not using the main sample of hydrogen peroxide. Avoid accidental contamination of solutions which may speed up the formation of oxygen and pressure build-up.

Source: Made by Author

Ethical Concerns

There are no ethical concerns associated with my experiment or the decomposition of hydrogen peroxide.

Environmental Concerns

Table 5: Shows environmental concerns and control measures for compounds used.

Compound	Environmental risks	Control measures
Hydrogen peroxide	Large amounts of hydrogen peroxide can harm microscopic algae, like phytoplankton, that feed everything from small fish to shrimp to whales, and hence can cause long-term harm to aquatic life (Lin).	Since I am using a very dilute hydrogen peroxide solution, this is not a big concern. However, just for safety, ensure that the hydrogen peroxide is disposed properly after the experiment.

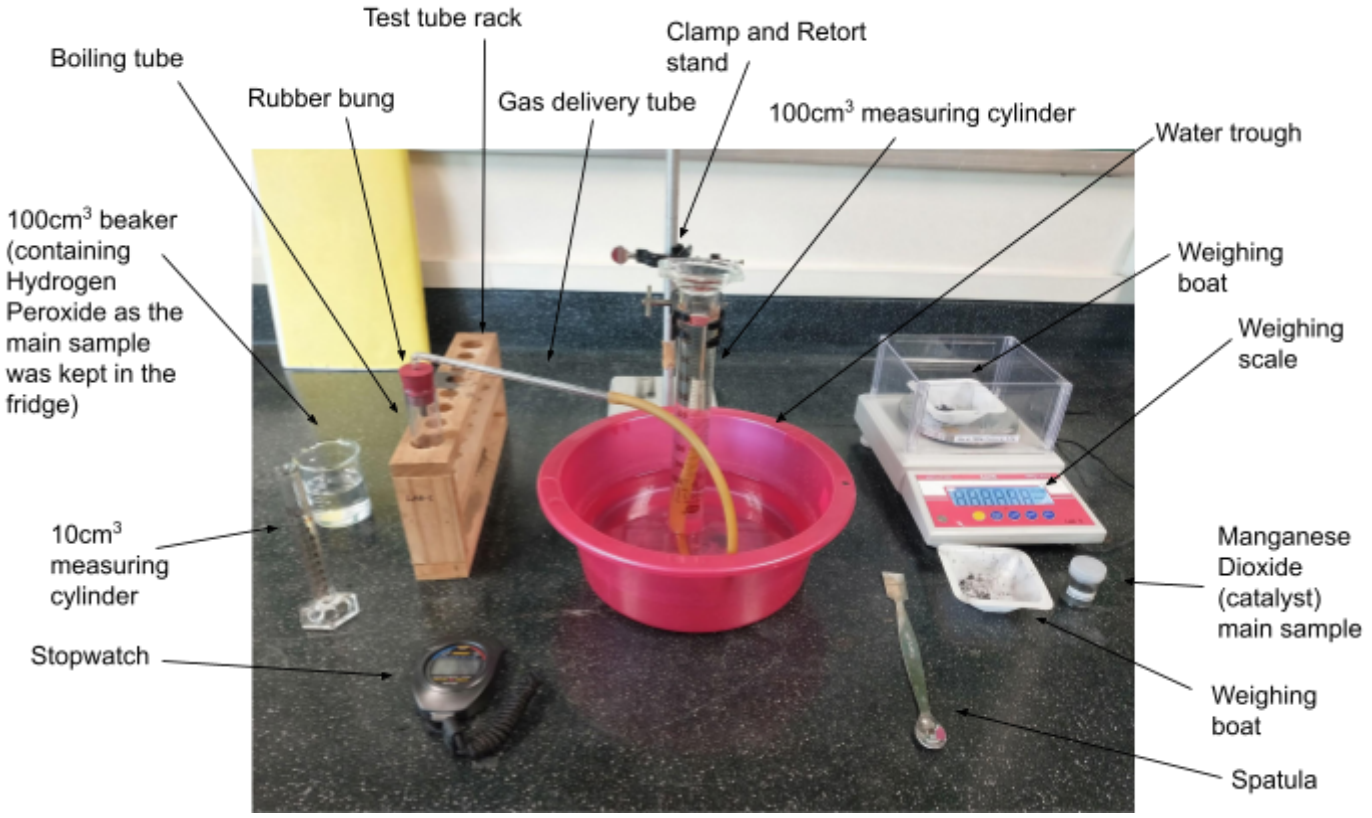
Source: Made by Author

Methodology

Apparatus setup

1. Thoroughly wash all the apparatus being used and set up the apparatus like the following:

Figure 3: Shows the setup of my apparatus for my experiment



Source: Picture taken by Author

Note: To set up the 100cm^3 measuring cylinder like in Figure 3, do the following:

a) Fill the 100cm^3 measuring cylinder with 90cm^3 of water (±1cm^3). Cover the open end fully with your hand and then flip the measuring cylinder upside down so that the open end is facing down.
b) Place the measuring cylinder upside down in the water trough. The open end must be facing down and fully submerged in the water trough so that no water can escape the 100cm^3 measuring cylinder.
c) Leave a small gap in between the bottom of the water trough and the open end of the measuring cylinder so that the open end of the rubber bung can go through the measuring cylinder.
d) Clamp the measuring cylinder to the retort stand so that it is held in place, like in Figure 3.

2. Pour hydrogen peroxide into the 100cm^3 Beaker until it is full. Then, place the main hydrogen peroxide solution in the fridge and in the dark to prevent the solution from decomposing.

<u>Experiment method</u>

3. Put one weighing boat on the weighing scale and then set the weighing scale to zero grams. Then, using a spatula, add manganese dioxide into the weighing boat until the weighing scale shows 0.1g (±0.01g). If excess manganese dioxide is added, remove the excess from the weighing boat on the weighing scale and put it on the second weighing boat on the side. **Do not** add the excess manganese dioxide back into the main container as this will contaminate the main sample.
4. Pour the 0.1g of manganese dioxide in the weighing boat into the boiling tube.
5. Pour 5cm^3 of hydrogen peroxide from the beaker into the 10cm^3 measuring cylinder (±0.2cm^3). If excess is poured into the measuring cylinder, **do not** pour the excess back into the main solution. Pour the excess back into the beaker so the main solution is not contaminated.

6. Start the stopwatch
7. As the stopwatch reaches 10 seconds (±0.01s), pour the $5cm^3$ of hydrogen peroxide, which is currently in the measuring cylinder, into the boiling tube and immediately cover the boiling tube fully with the rubber stopper by putting the rubber stopper inside the boiling tube. Gently shake the boiling tube. The reason for waiting ten seconds is because it is not possible to simultaneously start the stopwatch and cover the boiling tube with the rubber stopper at the same time. If I attempted to do this, some oxygen would have been released, thus affecting the accuracy of my results.
8. Record the volume of oxygen gas produced every 20 seconds, for 480 seconds (±0.01s).
9. Stop recording the volume of oxygen gas produced and stop the stopwatch after 480 seconds have passed (±0.01s). The stopwatch should show 490 seconds (8 minutes and 10 seconds) because I waited for the first 10 seconds.
10. Remove the rubber bung from the boiling tube.
11. Properly dispose of the magnesium dioxide and water in the boiling tube.
12. Repeat steps 1-11 two more times.
13. Repeat steps 1-12, but change the mass of the catalyst in step 3 to 0.2g, 0.3g, 0.4g, 0.5g, 0.6g, 0.7g and 0.8g (±0.01g).

Raw Data

Table 6: Shows the raw data that I collected for my experiment

	Volume of Oxygen gas produced when the mass of the catalyst (Manganese Dioxide) is… / (cm^3) (±1)																							
	… 0.1 (g) (±0.01)			… 0.2 (g) (±0.01)			… 0.3 (g) (±0.01)			… 0.4 (g) (±0.01)			… 0.5 (g) (±0.01)			… 0.6 (g) (±0.01)			… 0.7 (g) (±0.01)			… 0.8 (g) (±0.01)		
Time / (s) (±0.01)	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	12	10	11	13	12	14	18	19	18	23	24	22	28	26	29	28	29	27	30	26	30	29	29	27
40	20	18	19	24	24	25	32	31	30	41	40	40	50	49	50	48	49	46	48	47	51	46	50	47
60	26	26	25	33	32	33	40	39	38	53	53	52	64	62	63	63	63	61	63	62	62	60	61	60
80	32	31	30	40	39	41	47	46	45	61	59	58	70	68	67	69	69	68	69	67	68	68	69	67
100	36	36	35	46	45	47	53	52	50	65	64	62	72	70	69	71	70	69	71	69	70	70	71	70
120	41	41	40	50	50	51	57	57	56	67	66	66	73	71	70	72	71	71	71	70	72	72	71	72
140	44	45	44	54	54	54	60	62	61	68	68	69	73	73	71	72	72	73	72	71	73	73	73	73
160	48	48	47	58	57	57	64	65	65	69	69	71	74	73	73	73	72	74	74	71	73	73	73	73
180	51	51	50	60	60	59	67	67	68	70	71	72	74	74	73	73	73	74	74	73	74	74	73	74
200	54	53	53	62	62	61	69	68	70	71	71	73	74	74	74	74	73	74	74	73	74	74	74	74
220	56	55	56	64	63	62	70	69	70	72	71	73	74	74	74	74	73	74	74	74	74	74	74	74
240	58	57	59	65	64	63	70	70	70	72	72	73	74	74	74	74	74	74	74	74	74	74	74	74
260	60	58	61	66	65	64	71	70	71	73	72	73	74	74	74	74	74	74	74	74	74	74	74	74
280	61	60	62	66	66	65	71	71	71	73	72	73	74	74	74	74	74	74	74	74	74	74	74	74
300	62	61	63	68	67	66	72	71	71	73	72	73	74	74	74	74	74	74	74	74	74	74	74	74
320	63	62	63	68	67	67	72	71	71	73	73	73	74	74	74	74	74	74	74	74	74	74	74	74
340	64	63	64	68	68	67	72	72	72	73	73	73	74	74	74	74	74	74	74	74	74	74	74	74
360	65	64	64	69	68	68	72	72	72	73	73	73	74	74	74	74	74	74	74	74	74	74	74	74
380	66	65	65	69	68	68	72	72	72	73	73	73	74	74	74	74	74	74	74	74	74	74	74	74
400	66	65	66	69	68	69	72	72	72	73	73	73	74	74	74	74	74	74	74	74	74	74	74	74
420	67	66	66	69	68	69	72	72	72	73	73	73	74	74	74	74	74	74	74	74	74	74	74	74
440	67	66	66	69	68	69	72	72	72	73	73	74	74	74	74	74	74	74	74	74	74	74	74	74
460	67	66	67	69	68	69	72	72	72	73	73	74	74	74	74	74	74	74	74	74	74	74	74	74
480	67	66	67	69	68	69	72	72	72	73	73	74	74	74	74	74	74	74	74	74	74	74	74	74

Source: Made by Author

Qualitative observations

- Black foam and fog was produced due to the water and manganese dioxide physically mixing.
- During the transfer of substances, there was always a little bit of hydrogen peroxide left in the measuring cylinder and a little bit of manganese dioxide left in the weighing boat.

Sample calculations and error propagation

Table 7: Shows the sample calculation to find the average rate of decomposition of hydrogen peroxide when the mass of the catalyst, manganese dioxide, is 0.7g

Calculations	Error propagation
1. Find the average volume of oxygen gas produced at each time interval	
Average volume of oxygen gas produced when time is… $0s \rightarrow (0 + 0 + 0) \div 3 = 0cm^3$ $20s \rightarrow (30 + 26 + 30) \div 3 \approx 28.7cm^3 \approx 29cm^3$ $40s \rightarrow (48 + 47 + 51) \div 3 \approx 48.7cm^3 \approx 49cm^3$ $60s \rightarrow (63 + 62 + 62) \div 3 \approx 62.3cm^3 \approx 62cm^3$ $80s \rightarrow (69 + 67 + 68) \div 3 = 68cm^3$ $100s \rightarrow (71 + 69 + 70) \div 3 = 70cm^3$ $120s \rightarrow (71 + 70 + 72) \div 3 = 71cm^3$ $140s \rightarrow (72 + 71 + 73) \div 3 = 72cm^3$ $160s \rightarrow (74 + 71 + 73) \div 3 \approx 72.7cm^3 \approx 73cm^3$ $180s \rightarrow (74 + 73 + 74) \div 3 \approx 73.7cm^3 \approx 74cm^3$ $200s \rightarrow (74 + 73 + 74) \div 3 \approx 73.7cm^3 \approx 74cm^3$ $220s\ till\ 480s \rightarrow (74 + 74 + 74) \div 3 = 74cm^3$ Each volume is rounded to the same number of decimal places as its respective uncertainty.	The uncertainty for the average volume of oxygen gas produced can either be calculated by using the apparatus' uncertainties, or can be taken as the range divided by 2 when calculating averages. I have taken the higher value of the 2. Each of the following uncertainties is rounded to one significant figure. The uncertainty when using… apparatus uncertainty is: $\frac{1+1+1}{3} = 1cm^3$ range divided by 2 is: $0s \rightarrow (0 - 0) \div 2 = 0cm^3$ $20s \rightarrow (30 - 26) \div 2 = 2cm^3$ $40s \rightarrow (51 - 47) \div 2 = 2cm^3$ $60s \rightarrow (63 - 62) \div 2 = 0.5cm^3$ $80s \rightarrow (69 - 67) \div 2 = 1cm^3$ $100s \rightarrow (71 - 69) \div 2 = 1cm^3$ $120s \rightarrow (72 - 70) \div 2 = 1cm^3$ $140s \rightarrow (73 - 71) \div 2 = 1cm^3$ $160s \rightarrow (74 - 71) \div 2 = 1.5cm^3 \approx 2cm^3$ $180s\ and\ 200s \rightarrow (74 - 73) \div 2 = 0.5cm^3$ $220s\ till\ 480s \rightarrow (74 - 74) \div 2 = 0cm^3$ The apparatus uncertainty is bigger or the same as the range divided by two for all time intervals except when time is 20s, 40s, and 160s. For these three time intervals, the range divided by 2 will be used as their uncertainty.
2. Find the average rate of decomposition by dividing the total average volume of oxygen gas produced by the time at which that volume of oxygen gas was first produced	
The total average volume of oxygen produced for when the mass of the catalyst is 0.7g is: $74cm^3$ The shortest time taken to produce an average of $74cm^3$ of oxygen gas: 180 seconds The average rate of the decomposition reaction is: $74 \div 180 \approx 0.411cm^3/s$	The uncertainty for when the average volume of gas is $74cm^3$ is $\pm 1cm^3$, and the uncertainty for the average amount of time taken is ± 0.01s. I know that if $y = \frac{ab}{c}$, then $\Delta y = (\frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c}) * y$ Hence, the total uncertainty for the average rate of the decomposition reaction is as follows: $(\frac{1}{74} + \frac{0.01}{180}) \times 0.411 \approx 0.006cm^3$
Final answer with absolute error $\approx 0.411cm^3/s \pm 0.006cm^3$	

Source: Made by Author

Processed Data

Table 8: Shows the processed data for the average volume of oxygen gas produced at regular time intervals

	Average volume of Oxygen gas produced when the mass of the catalyst (Manganese Dioxide) is... / (cm^3)							
Time / (s) (±0.01)	... 0.1 (g) (±0.01)	... 0.2 (g) (±0.01)	... 0.3 (g) (±0.01)	... 0.4 (g) (±0.01)	... 0.5 (g) (±0.01)	... 0.6 (g) (±0.01)	... 0.7 (g) (±0.01)	... 0.8 (g) (±0.01)
0	0 ± 1	0 ± 1	0 ± 1	0 ± 1	0 ± 1	0 ± 1	0 ± 1	0 ± 1
20	11 ± 1	13 ± 1	18 ± 1	23 ± 1	28 ± 2	28 ± 1	29 ± 2	28 ± 1
40	19 ± 1	24 ± 1	31 ± 1	40 ± 1	50 ± 1	48 ± 2	49 ± 2	48 ± 2
60	26 ± 1	33 ± 1	39 ± 1	53 ± 1	63 ± 1	62 ± 1	62 ± 1	60 ± 1
80	31 ± 1	40 ± 1	46 ± 1	59 ± 2	68 ± 2	69 ± 1	68 ± 1	68 ± 1
100	36 ± 1	46 ± 1	52 ± 2	64 ± 2	70 ± 2	70 ± 1	70 ± 1	70 ± 1
120	41 ± 1	50 ± 1	57 ± 1	66 ± 1	71 ± 2	71 ± 1	71 ± 1	72 ± 1
140	44 ± 1	54 ± 1	61 ± 1	68 ± 1	72 ± 1	72 ± 1	72 ± 1	73 ± 1
160	48 ± 1	57 ± 1	65 ± 1	70 ± 1	73 ± 1	73 ± 1	73 ± 2	73 ± 1
180	51 ± 1	60 ± 1	67 ± 1	71 ± 1	74 ± 1	73 ± 1	74 ± 1	74 ± 1
200	53 ± 1	62 ± 1	69 ± 1	72 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
220	56 ± 1	63 ± 1	70 ± 1	72 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
240	58 ± 1	64 ± 1	70 ± 1	72 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
260	60 ± 2	65 ± 1	71 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
280	61 ± 1	66 ± 1	71 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
300	62 ± 1	67 ± 1	71 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
320	63 ± 1	67 ± 1	71 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
340	64 ± 1	68 ± 1	72 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
360	64 ± 1	68 ± 1	72 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
380	65 ± 1	68 ± 1	72 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
400	66 ± 1	69 ± 1	72 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
420	66 ± 1	69 ± 1	72 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
440	66 ± 1	69 ± 1	72 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
460	67 ± 1	69 ± 1	72 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1
480	67 ± 1	69 ± 1	72 ± 1	73 ± 1	74 ± 1	74 ± 1	74 ± 1	74 ± 1

Source: Made by Author

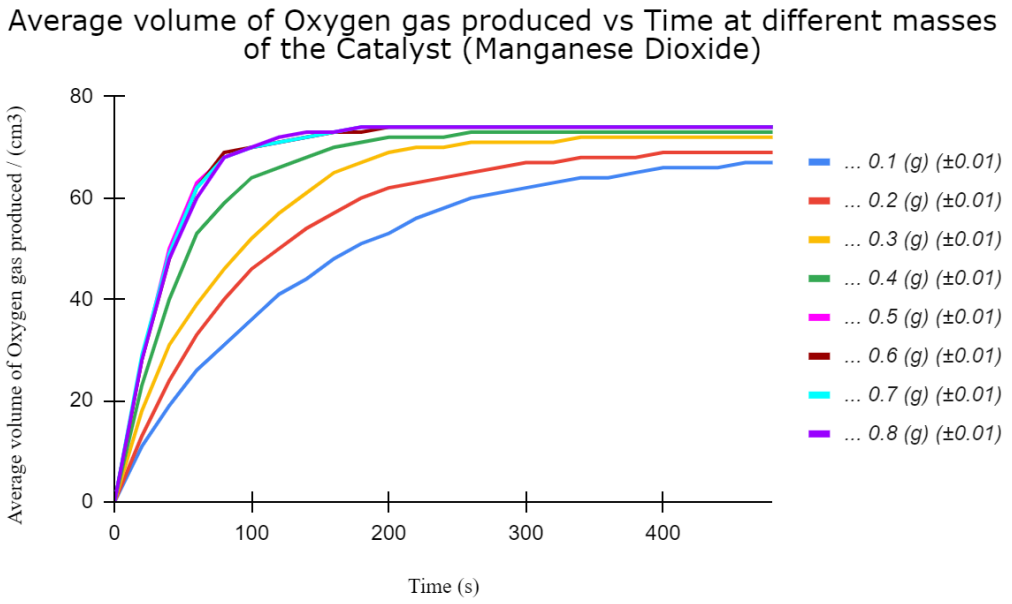
Table 9: Shows the processed data for the average rate of decomposition of hydrogen peroxide

Mass of catalyst (manganese dioxide) / (g) (±0.01)	Time taken to finish reaction / (s) (±0.01)	Volume of oxygen gas produced / (cm^3) (±1)	Average rate of the decomposition reaction / (cm^3/s)
0.1	460	67	0.146 ± 0.002
0.2	400	69	0.173 ± 0.003
0.3	340	72	0.212 ± 0.003
0.4	260	73	0.281 ± 0.004
0.5	180	74	0.411 ± 0.006
0.6	200	74	0.370 ± 0.005
0.7	180	74	0.411 ± 0.006
0.8	180	74	0.411 ± 0.006

Source: Made by Author

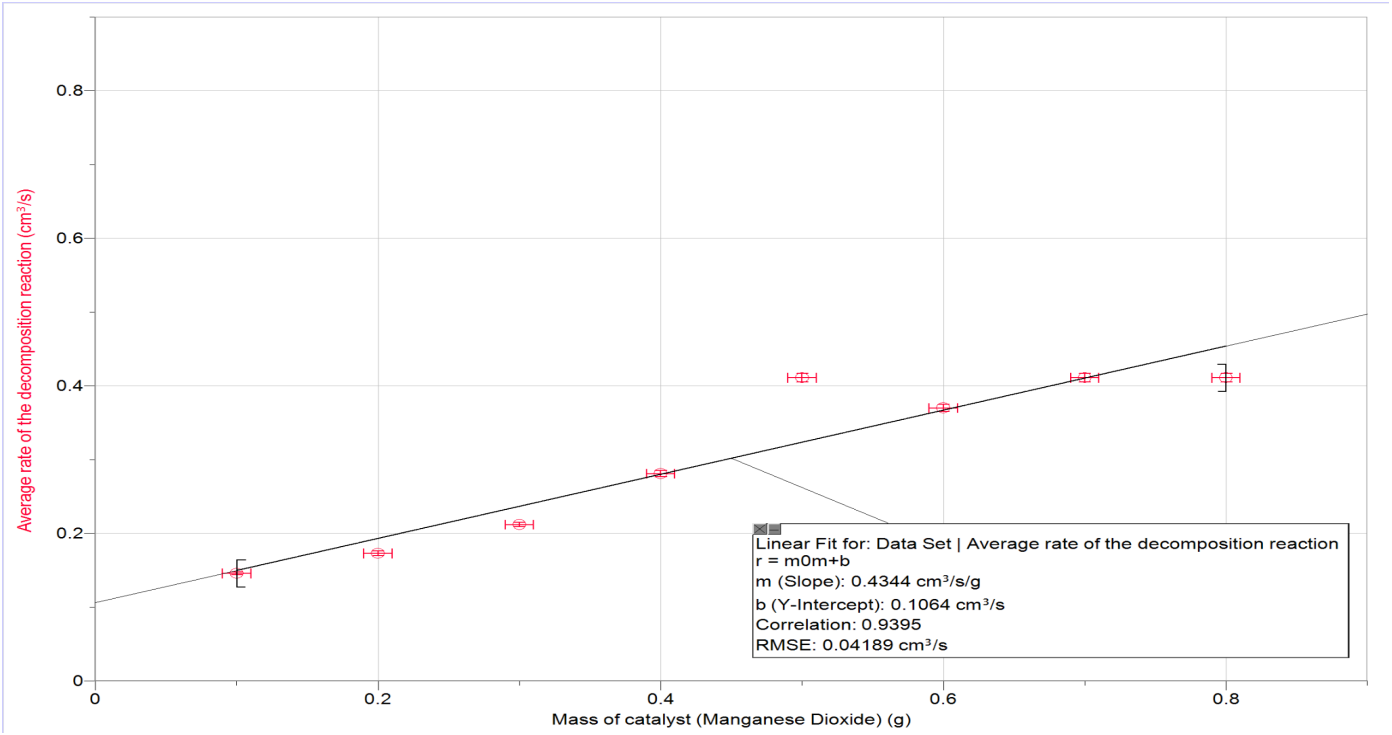
Graph

Graph 1: Shows the processed data in table 8 on a graph



Source: Made by Author

Graph 2: Shows the processed data in table 9 on a graph



Source: Made by Author

Conclusion

In conclusion, I found that there is a relationship between the mass of the catalyst, manganese dioxide, and the average rate of the decomposition reaction of hydrogen peroxide. However, this relationship only exists for small masses of manganese dioxide. As can be seen in Graph 2, the average rate of the decomposition reaction increases as the mass of the catalyst increases up until the mass of the catalyst is 0.5g. After this, as the mass of the catalyst increases, the average rate of reaction is not changed, and actually decreases for when the mass of the catalyst is 0.6g (although this may be due to experimental error). This trend can

also be seen in Graph 1. Graph 1 plots the average volume of oxygen gas produced over time and hence in this graph, the rate of the decomposition reaction is the gradient. The first five lines representing the mass of the catalyst being 0.1g, 0.2g, 0.3g, 0.4g, and 0.5g are clearly seen and the gradient increases as the mass increases for these five resulting in the reaction being completed quicker. However, after this, the gradient of the line and the time taken for the decomposition reaction to be completed approximately stays the same when the mass of the catalyst increases to 0.6g, 0.7g and 0.8g. Hence, both Graph 1 and Graph 2 show that a relationship exists between the mass of the catalyst manganese dioxide and the rate of the decomposition reaction of hydrogen peroxide. However, this only exists when the mass of manganese dioxide used is small, specifically less or equal to 0.5g.

This was not what I expected and hypothesised, as the mass of the catalyst should not affect the rate of a reaction. However, it is possible that this is still the case as one reason as to why my results show that there is a relationship between the mass of manganese dioxide and the average rate of the decomposition reaction may be because at lower masses of the catalyst, physical properties of the catalyst may have affected the rate of the reaction. One such property is surface area, which may have changed as I changed the mass of the catalyst. To increase the mass of manganese dioxide, each time I was adding more powdered manganese dioxide. This could have increased the surface area of the catalyst as more powder may have been dispersed in the boiling tube resulting in a larger surface area of the catalyst too. An increase in the surface area of the catalyst increases the rate of the reaction as there are more particles and active sites at the surface that can react simultaneously with the reactants, thus increasing the amount of collisions per time period, thus increasing the rate of the reaction. Catalysts are only active towards reactants on specific locations which possess catalytic activity, known as active sites. For the catalyst to speed up the rate of the reaction, the catalyst must associate with the reactant molecules using active sites which are on the catalyst's surface (Weckhuysen et al). In the case of a solid catalyst, the number of active sites available are highly dependent on the surface area of the solid catalyst and increasing the surface area of the catalyst also increases the active sites available that can react with the reactant particles (Elsevier). In the case of dispersed catalysts, such as manganese dioxide powder, the rate of the reaction is proportional to the catalytic sites exposed as more active sites available leads to more reactant molecules undergoing adsorption at the same time, resulting in more successful decompositions per time period, thus increasing the rate of decomposition of hydrogen peroxide.

This explains why a relationship is seen between the mass of the catalyst and the average rate of decomposition of hydrogen peroxide. Furthermore, a reason why this relationship is not seen for higher masses of the catalyst could be because when the mass of the catalyst was 0.5g, the surface area was already big enough such that there was an excess amount of active sites available for all of the hydrogen peroxide to react with, and hence when the mass of the catalyst increased to 0.6g, 0.7g, 0.8g, the increase in surface area did not affect the rate of the decomposition reaction of hydrogen peroxide. It is also possible that as the mass increases from 0.5g onwards, the surface area does not increase as the powder may have stacked up on top of each other instead of being dispersed in the boiling tube.

It is also possible that my results are inaccurate and this may be another reason as to why my hypothesis was incorrect. However, this is unlikely as I have repeated my results three times, and obtained very similar results each time leading to a very low absolute uncertainty for the average rate of the decomposition reaction. Thus, I have relatively high confidence in my results. It is also possible that a systematic error has occurred, leading to all my points being inaccurate despite a low uncertainty. However, this is also unlikely because if this were to happen, it would have shifted all my data points equally, which would ultimately still show the same relationship. In my evaluation I discuss other limitations and strengths of my investigations.

Evaluation

Table 10: Shows limitations to the data collected and possible improvements

Error	Significance	Improvement
There was still hydrogen peroxide and manganese dioxide left in the measuring cylinder and weighing boat respectively after transferring it to the boiling tube.	This resulted in systematic error that could affect the rate of the reaction. However, the significance is low because the amount transferred was relatively large compared to the volume/amount left in the apparatus.	Minimise the number of times liquids are transferred and as far as possible, transfer liquids only once.

For the lower masses of the catalyst, even after 480 seconds oxygen gas was still being produced, albeit at a very low rate.	This means that the reaction may not have been completed yet, and hence the average rate of reaction that I have calculated may be inaccurate. This also gives an explanation as to why the volume of oxygen gas produced is different for the first five masses of manganese dioxide.	Observe the reaction for 600 seconds, which is more than 480 seconds, so that the reaction is complete.
It is possible that I may have not measured the volume of oxygen gas produced exactly every 20 seconds as there would have been lag time in between checking the stopwatch and reading the volume of oxygen gas produced in the measuring cylinder	Raw data may not be completely accurate and hence, the rate of the reaction calculated may not be fully accurate.	Video the oxygen gas being produced in the measuring cylinder with a stopwatch next to it, so that I can pause the video exactly every 20 seconds and measure the volume of oxygen gas produced accurately.
Only 3 trials were done for each mass of the catalyst	3 trials can be considered insufficient and could result in low reliability and accuracy in results, increasing random error.	Do 5 to 10 trials instead.

Source: Made by Author

Table 11 : Shows the strengths of the investigation

Strengths	Significance
Accurate and the same equipment was used for all trials.	This minimises systematic error as keeping the apparatus used consistent improves the accuracy and precision of results.
The experiment was carried out with 8 different masses for the catalyst (independent variable).	This gives a wider range of data which provides a more detailed and informed trend.
All 24 trials were taken from the same standard solutions.	This maintained consistency in the solutions used throughout the experiment to reduce random error.

Source: Made by Author

Extension

To fully understand the relationship between the mass of a catalyst and the average rate of the decomposition of hydrogen peroxide, further extensions can be carried out. Firstly, I can increase the range of masses of the catalyst so that the highest mass of the catalyst in my experiment is more than 1 gram. This will help conclusively prove whether the mass of the catalyst affects the decomposition reaction. This is because I concluded that the mass of the catalyst only affects the rate of the reaction at smaller masses and so if my explanation in my conclusion is true, then higher masses of the catalyst should not affect the rate of the reaction. Thus, this can help conclusively prove or disprove my explanation in the conclusion.

Another possible extension is to investigate the effect of different catalysts, such as lead oxide and catalase, on the rate of decomposition of hydrogen peroxide, and evaluate whether changes in the mass of these catalysts produce the same results as I have collected with manganese dioxide.

I could also investigate other factors, such as temperature, that affect the rate of decomposition of hydrogen peroxide. Investigating the effect of temperature would also allow me to calculate the activation energy for this reaction, which I could compare to literature values. This could be done for numerous catalysts, allowing me to compare the activation energy of the reaction with different catalysts.

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