How do different catalysts and concentrations affect the rate order of hydrogen peroxide decomposition?

Introduction

One of the simplest, yet useful compounds found in chemistry is hydrogen peroxide. Being an extremely effective corrosive agent and oxidiser, I have come across peroxide in both my interest in aerospace engineering, as a hypergolic fuel reacting without ignition and in my job as a health worker, being the primary disinfectant used for treating any wound. However, hydrogen peroxide has a tendency to decompose into water and oxygen, despite the conditions it is kept under. This is disastrous for any application, as the peroxide's effects as an oxidiser or disinfectant rely on its concentration. Therefore, it is imperative to find the conditions under which hydrogen peroxide decomposes slowest. So, here is the question:

How do different catalysts and concentrations affect the rate order of hydrogen peroxide decomposition?

Background information

Hydrogen peroxide is a non-organic peroxide, that is commonly used in industrial processes as an oxidising agent. Hydrogen peroxide is formed of two hydroxyl groups, with a O-O bond completing the structure of the molecule. This bond is unstable, and results in hydrogen peroxide gradually decomposing over time through the reaction:

$$H_2O_2 \rightarrow 2OH$$

$$OH + H_2O_2 \rightarrow H_2O + HO_2$$

$$OH + HO_2 \rightarrow H_2O + O_2$$

This can be expressed in the reaction:

$$2H_2O_2 \rightarrow O_2 + H_2O$$

This reaction produces an extreme amount of heat (ΔH=-2884.5 kJ/kg H_2O_2 when decomposing in a pure H_2O_2 solution), because of the high stability of H_2O, and unfavourable nature of the peroxide bond. This bond is so unstable that it will undergo decomposition under all conditions. Although we are unable to entirely prevent its decay, controlling the surroundings and conditions of a hydrogen peroxide solution can slow the decomposition reaction. The factors that affect the decomposition of H_2O_2 are:

- Temperature - All chemical reactions accelerate with an increase in temperature, as a particle having a higher velocity result in more frequent collisions. However, because hydrogen peroxide's decomposition is an exothermic reaction, the rate of reaction accelerates exponentially, since more reaction creates more heat, accelerating the decomposition. This leads to runaway situations where Hydrogen peroxide explodes if heated too high (typically high concentrations of hydrogen peroxide are unstable above 323K).
- Exposure to light - Ultraviolet light is strong enough to provide the necessary energy to break the O-O bond in hydrogen peroxide through a process known as photolysis. By shining high energy light onto it, we create two hydroxyl radicals that can then bond

into oxygen and water. This is important since the necessary wavelength of light (<405nm) needed to photolyse this reaction is found in sunlight and certain lightbulbs.

- Concentration - hydrogen peroxide's rate of decomposition accelerates when a higher concentration of it is in solution, even when kept at a constant temperature. Because the decomposition of hydrogen peroxide requires two molecules to fully decompose, having more peroxide to collide with increases the rate of decomposition.
- Catalysts - certain catalysts like potassium iodide, potassium permanganate and manganese dioxide are able to decompose hydrogen peroxide through a different process to its automatic process. For example, when potassium iodide reacts with peroxide, it undergoes the following reaction:

$$2I^- + H_2O_2 \rightarrow I_2 + 2OH^-$$

$$I_2 + H_2O_2 \rightarrow 2I^- + 2H^+ + O_2$$

$$2OH^- + 2H^+ \rightarrow 2H_2O$$

This secondary reaction pathway for the decomposition of hydrogen peroxide increases the rate of reaction, as there is more than one potential collision to begin a reaction (colliding with another H_2O_2 molecule, or an iodine ion).

- Acidity - As the natural and catalysed decomposition of hydrogen peroxide use hydroxide ions or hydroxyl radicals basic solutions have the ability to interfere with the natural breakdown of peroxide. Creating more hydroxyl molecules (or ions) to interact with increases the chance of collision with a peroxide molecule, therefore accelerating the rate of reaction.

For this experiment, we will only be finding the effects of changing the concentration and catalysts within hydrogen peroxide. Controlling the temperature of hydrogen peroxide to affect its rate of reaction would be extremely dangerous, because of the possibility of a cook off. I will not be able to measure the amount of light impacting a hydrogen peroxide container, both because of our labs not having a photometer, and it being infeasible to prevent contamination from other light sources without a very dark room.

The amount of hydrogen peroxide that decomposes within this reaction can be measured, through a gas cylinder. As oxygen gas is released by this decomposition reaction, we can measure the volume of oxygen released to get an exact value for how much hydrogen peroxide has decomposed at a set point in time. By plotting these volume values against time on a graph, we can determine the effect of altering one of the conditions of our decomposition experiment.

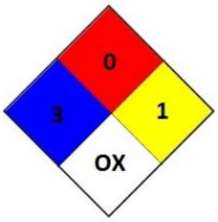
Controlled variables

Controlled Variable	Explanation	Method of control
Temperature of solution	Temperature can affect the rate of decomposition, as this experiment will not test for it, it is necessary to control it.	Ensuring Peroxide is stored at a standard temperature, not left in direct sunlight, ensure fridge temperature is controlled (277.15K)

Mass of catalyst	Because the mass of the catalyst affects the surface area presented to the peroxide, controlling mass is important to compare results	Measure mass before each reaction of catalysts. Ensure mass is similar
Acidity of solution	Hydroxyl radicals and ions from basic solutions are able to perform the second stage of natural peroxide decomposition, which changes the rate of decomposition	When diluting Peroxide, only use distilled water to keep solution at pH 7.
Exposure to light	Hydrogen peroxide’s innate property of photolysis under exposure to common frequencies of light means different intensities can result in variations in rate of reaction.	Close blinds facing experiment, and only use artificial lights for illuminating lab. Intensity is controlled so no effect is applied on rate of reaction between experiments.
Exposure to organic compounds	Catalase is an enzyme within the body that specifically accelerates the decomposition of hydrogen peroxide. Contamination of peroxide via touch could affect the rate of reaction.	Ensure thorough cleaning of all reaction containers before usage, and wear gloves to prevent cross contamination.

Apparatus and equipment

Apparatus	Materials
100 cm^3 gas cylinder (graduated in 1 cm^3 increments) 2 x Equipment stand Several conical flasks (500ml) Several boiling tubes Scales (accurate to the nearest mg) Weigh boats Small spatula Plastic pipette Rubber stoppers (for wide and narrow flasks) Rubber tube Measuring cylinders (graduated to nearest ml)	100 vol hydrogen peroxide (l) 100g Potassium permanganate (s) 100g Potassium iodide (s) 100g Manganese dioxide (s) 1L Distilled water (aq)

Chemical	Hazard statements	NFPA 704 & Hazard symbol	Precautions taken	Emergency instructions
Hydrogen peroxide (H_2O_2)	oxidiser, corrosive to skin, harmful if ingested,	 	Store away from organic materials, keep at low temperatures. Wear gloves, googles and lab clothing when handling.	If in contact with skin, immediately rinse for 15 minutes affected area and surrounding skin. Remove all jewellery near affected area. If in contact with eyes proceed to eye wash station and flush eyes. Seek medical attention. If ingested do not induce vomiting. Rinse mouth with water only if affected person is conscious. Seek medical attention immediately. If inhaled exit lab and seek fresh air, seek medical assistance.
Manganese dioxide (MnO_2)	Harmful if swallowed. Harmful if inhaled.		Avoid contact with skin, use gloves when handling. Wear eye protection. Wear protective clothing	If inhaled loosen clothing as necessary and seek fresh air. Give artificial respiration or oxygen if breathing is laboured / difficult. Seek medical attention. If in contact with skin, rinse affected area for 15 minutes with cold water. Seek medical advice if irritation persists. Upon eye contact rinse eyes using eye

				wash station. Remove contact lenses if present. Seek medical attention if irritation persists. If swallowed do not induce vomiting. Rinse mouth using clean water and try to get exposed individual to drink sips of water if conscious.
Potassium Permanganate	Oxidizer. Harmful if swallowed. Causes severe skin burns and eye damage. Very toxic to aquatic life with long lasting effects.	    	Wash hands after handling. Avoid contact with skin and eyes. Discard contaminated materials.Avoid contact with skin, eyes, and clothing.	If inhaled, move exposed to fresh air. Give artificial respiration if necessary. If breathing is difficult give Oxygen. Loosen clothing and place exposed in a comfortable position.Seek medical assistance if cough or other symptoms appear. If in contact with skin, immediately enter emergency shower rinsing while removing contaminated clothing and shoes. Immediately seek medical attention.Wash hands and exposed skin with soap and plenty of water. If in contact with eye, Immediately seek medical attention. continue rinsing eyes during transport to the Hospital. Protect unexposed eye. Flush exposed eye gently using water for 15-20 minutes. Remove

				contact lenses while rinsing. If swallowed, rinse mouth with water. Do not induce vomiting. Never give anything by mouth to an unconscious person. Immediately seek medical attention
Potassium Iodide	Causes serious eye irritation. Causes skin irritation	 	Wear protective equipment. Use respiratory protective device against the effects of fumes/dust/ aerosol. Keep unprotected persons away. Ensure adequate ventilation	If inhaled, move exposed individual to fresh air. Loosen clothing as necessary and position individual in a comfortable position.Seek medical advice if discomfort or irritation persists.If breathing difficult, give oxygen. If in contact with skin, wash affected area with soap and water. Rinse thoroughly. Seek medical attention if irritation persists or if concerned. If swallowed rinse mouth thoroughly. Do not induce vomiting. Have exposed individual drink sips of water. Seek medical attention if irritation, discomfort or vomiting persists.

Methodology

Initial preparation - create a 4.265 mol dm^{-3} hydrogen $peroxide_{(aq)}$ to remove possibility of spilling high concentration peroxide.

Prepare test stands - one with a clamp able to fit a beaker and boiling tube, one with a gas cylinder with rubber tubing, and a stopper able to fit onto beaker or boiling tube.

For measuring the effects of catalysts on hydrogen peroxide:

1. Prepare a 1% solution of hydrogen peroxide (0.4265 mol dm^{-3})
2. Pour $20cm^3$ of 1% hydrogen peroxide solution into a 500ml beaker, place on a test stand
3. Measure out 0.5g of catalyst
4. Add catalyst to the beaker of hydrogen peroxide, immediately put rubber stopper connected to gas cylinder on top of beaker
5. Start stopwatch.
6. At regular intervals record the change in volume of the gas cylinder, ensuring enough precision between measurements to give useful results

For measuring the effects of changing concentration on hydrogen peroxide with concentrations greater than 2%:

1. Prepare a solution of hydrogen peroxide, with set concentration and volume in excess of 15ml
2. Pour 5ml of solution into a boiling tube, clamped onto a test stand

3. Measure out approximately 0.220g of manganese dioxide into a weighing boat
4. Add manganese dioxide into boiling tube, immediately add rubber stopper onto boiling tube
5. Start stopwatch.
6. At regular intervals record the change in volume of the gas cylinder, ensuring enough precision between measurements to give useful results.

(For the potassium iodide measuring the rate of reaction difference between catalysts, a 5% concentration of peroxide was used in a 20 ml solution with 1 gram of catalyst to accelerate the reaction process)

Data

3 Runs of different catalysts ($KMnO_4$, KI & MnO_2) were recorded, giving 9 different results

3 Runs of different concentrations (1,2,5,7.5 & 10%) were recorded, giving 15 different results

Catalytic tests

	Run 1			Run 2			Run 3			Avg run data	
Catalyst used:	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:
MnO_2	30	10	0.56	30	10	0.55	30	15	0.562	30	11.66667
H_2O_2 1%	60	19.5		60	20		60	23		60	20.83333
vol: 20ml	90	25.5		90	30.5		90	31		90	29
	120	29		120	35		120	37.5		120	33.83333
	150	31		150	39.5		150	40.5		150	37
	180	33.5		180	42		180	44		180	39.83333

	240	36		240	46		240	47.5		240	43.16667
	300	37.5		300	47.5		300	49.5		300	44.83333
	360	37.5		360	47.5		360	50.5		360	45.16667

Catalyst used:	Run 1			Run 2			Run 3			Avg run data	
KI	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:
H2O2 5%	60	30	1.077	60	34	1.054	60	17	1.045	60	27
vol: 20ml	120	63.5		120	75		120	36		120	58.0
	180	89		180	100		180	59		180	82.5
	240	104		240	108.5		240	79		240	97.0
	300	109		300	110		300	91.5		300	103.5
	360	110		360	110		360	97		360	105.5
	420	110.5		420	110		420	99		420	106.5

Catalyst used:	Run 1			Run 2			Run 3			Avg run data	
KMnO4	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:
H2O2 1%	5	20	0.545	5	19	0.552	5	24	0.514	5	21.0
Vol: 20ml	10	33		10	29		10	40		10	34.0
	15	44		15	34		15	46		15	41.5
	20	46		20	37		20	48		20	43.5
	25	48		25	39		25	49		25	45.5
	30	49.5		30	40		30	49.5		30	46.5
	35	50		35	41		35	50.5		35	47.0
	40	50.5		40	41.5		40	51.5		40	48.0
	45	50.5		45	42		45	51.5		45	48.0
	50	50.5		50	43.5		50	51.5		50	48.5

	55	50.5		55	43.5		55	51.5		55	48.5
	60	51		60	44		60	51.5		60	49.0

Concentration Tests

Catalyst used:	Run 1			Run 2			Run 3			Avg run data	
MnO_2	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:
H_2O_2 2%	30	25	0.51	30	31	0.523	30	20.5	0.584	30	25.5
vol: 20ml	60	54		60	47.5		60	40.5		60	47.5
	90	70		90	62.5		90	65		90	66.0
	120	79		120	73.5		120	74		120	75.5
	150	87		150	80		150	81		150	82.5
	180	92		180	85		180	86.5		180	88.0
	240	95		240	89.5		240	92		240	92.0
	300	96.5		300	92		300	94		300	94.0
	360	96.5		360	92.5		360	94		360	94.5

Catalyst used:	Run 1			Run 2			Run 3			Avg run data	
MnO_2	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:
H_2O_2 5%	30	6.5	0.205	30	12	0.225	30	11	0.209	30	10.0
vol: 5ml	60	9.5		60	18		60	16		60	14.5
	90	11		90	22		90	21		90	18
	120	12.5		120	25		120	23		120	20.0
	150	14		150	27		150	25		150	22.0
	180	15		180	28		180	26		180	23.0

	240	17		240	28.5		240	27		240	24.0
	300	18.5		300	28.5		300	27		300	24.5
	360	20		360	28.5		360	27		360	25.0

MnO_2	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:
H_2O_2 7.5%	30	18	0.245	30	12	0.225	30	17	0.240	30	15.5
vol: 5ml	60	26		60	18		60	25.5		60	23.5
	90	30		90	22		90	29		90	27.0
	120	33.5		120	25		120	32		120	30.0
	150	36		150	27		150	33.5		150	32.0
	180	37		180	28		180	34.5		180	33.0
	240	40		240	28.5		240	35.5		240	34.5

MnO_2	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:	Mass:	Time:	Gas produced:
H_2O_2 10%	30	26	0.24	30	32.5	0.357	30	24	0.22	30	27.5
vol: 5ml	60	42		60	45		60	39		60	42.0
	90	52.5		90	51.5		90	48		90	50.5
	120	54		120	53		120	49.5		120	52.0
	150	55		150	53.5		150	50		150	53.0
	180	55		180	53.5		180	50		180	53.0
	240	55		240	53.5		240	50.5		240	53.0

For potassium Iodide reactions, a concentration of 5% was used in order to make the chemical reaction faster, so as to be measurable within a reasonable time frame.

Data Analysis

$$Average\ volume\ of\ Gas\ released\ =\ Sum\ of\ all\ runs\ /\ Number\ of\ runs$$

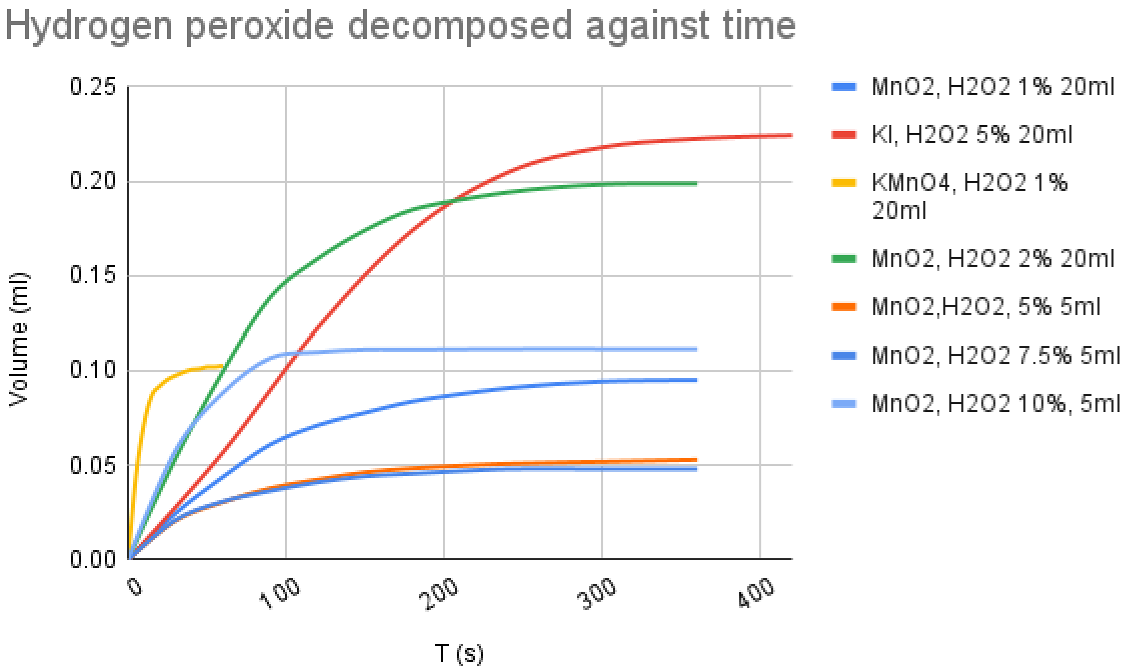
At Standard Temperature and Pressure, 1 mol (g) = 24 dm^3 volume, or 1mol(g) = 24,000cm^3.

The stoichiometric ratio between H_2O_2 & O_2 in peroxide's decomposition reaction is 2:1, so after division to find the molar number of oxygen, we multiply by 2 to gain the number of mols of peroxide. Once we have the molar volume of hydrogen peroxide, dividing it by the volume/mol (23.58 cm^3/mol) gives a final formula for the volume of H_2O_2 in relation to O_2:

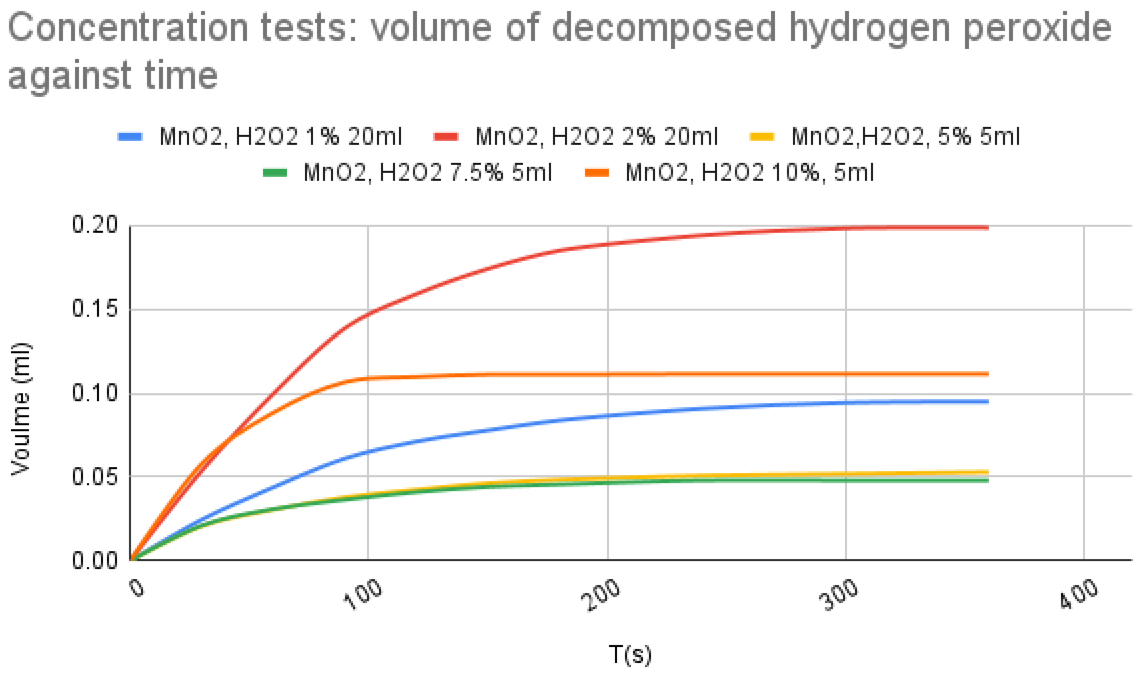
$$Mols\ H2O2 = 23.58V/11200$$

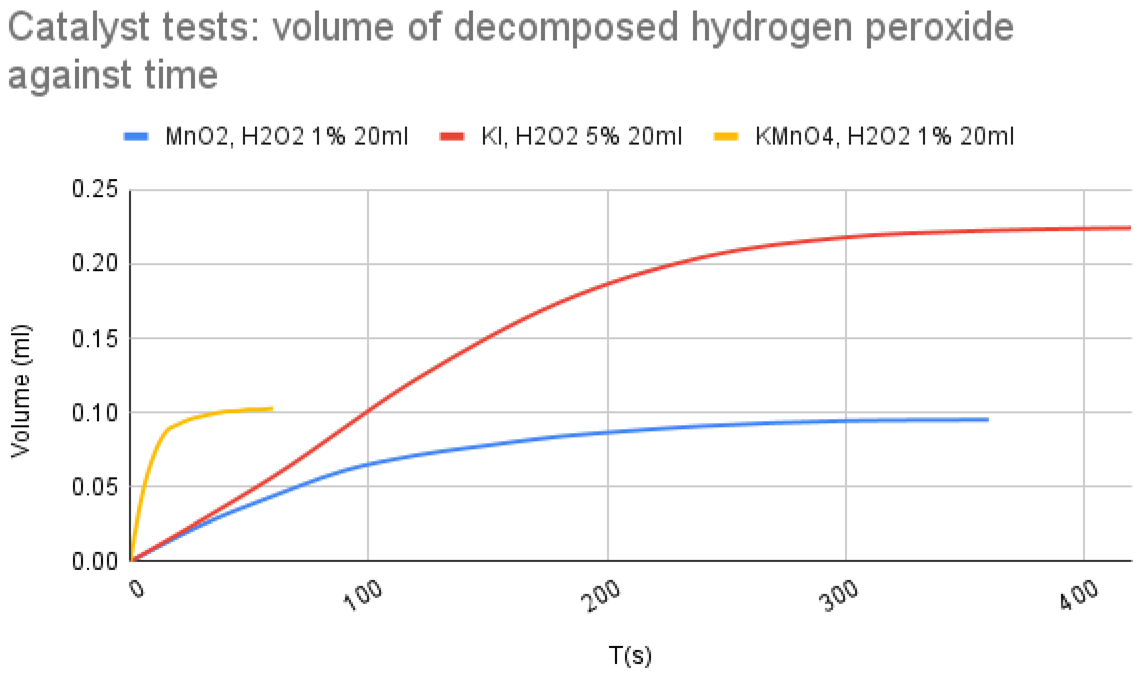
By applying this formula to all of the measured volumes of gas, we can therefore gauge how much peroxide reacted between intervals, and therefore model whether hydrogen peroxide does follow a first order reaction rate.

By inserting these values into google sheets, I generated a series of graphs of the decomposed hydrogen peroxide (in mols) against time (in seconds)



Along with graphs split between concentration tests, and catalyst tests





To compare the effects of the concentration and reaction, I will analyse them independently from each other. The concentration tests had their volume of reaction changed midway through experimental process (with the starting reaction volume being 20ml, and subsequent experiments after 2% being conducted with 5ml of peroxide), so these will also be compared independently, as factors such as surface area touching the mixing vessel and area exposed to the air against volume of the mixing solution could affect the rate of reaction as well. Observing the gas produced at 100s for 1% and 2% concentrations, I found an increase of 220% in terms of the gas produced, with a 210% increase at 200s. This is similar to the idea the definition of a first order increase, but using more data will help to increase certainty. Comparing the 5%, 10% reactions at 100s shows that between 5% and 10% indicate an increase of 265% in gas released, and an 240% at 200s. I will not be using the 7.5% experiment because it appears that it does not fit the data. It produces less gas than the 5% graph, so will be discounted for this analysis. Overall, by comparing set points it appears that the concentration of hydrogen peroxide is a first order reactant factor, as the results tend towards a doubling of gas produced in correlation to the concentration's changes.

Observing the experiments done using catalysts, there is a problem regarding the data range. When experimenting, it was found that KI failed to trigger a significant difference in the reaction speed of the hydrogen peroxide. Because of this, it was decided to increase the concentration to 5%. Going off the concentration data currently attained in this IA it will therefore be assumed that a 500% reduction in gas produced will be a reasonable figure to compare the reactions of the different catalysts. Using MnO_2 as a baseline, there was an observed 40% decrease using KI at 100s and 45% decrease at 200s. However, because there was twice as much potassium iodide as magnesium permanganate, these values are increased to 80% and 90%. For $KMnO_4$, it is impossible to do multiple comparisons because of the short time window the reaction occurred in, so I will only compare the 50s time frame. Here, potassium permanganate is 240% greater in volume produced than magnesium peroxide, and 780% greater than potassium iodide (with a doubling in the percentage because of the stated mass issue again). Here clearly we can see that the catalyst has an effect on the decomposition rate of hydrogen peroxide, with potassium iodide being the least reactive and potassium permanganate being the most.

Conclusion

The results from this IA indicate that concentration is a first order component of the decomposition of hydrogen peroxide, whilst catalysts have a significant effect on its decay. Concentration having a first order effect on the reaction rate is supported by the common literature around reaction rates, so that component of the IA was a success. However, although a comparison of catalysts was done, it was impossible to determine as to the effect catalysts have on the decay rate. This is because catalysts do not have a measurable analogue value that can be compared, however it was concluded that potassium permanganate accelerates peroxide's decay rapidly, whilst potassium permanganate is ineffective at breaking up the peroxide.

If I were to attempt this IA again, I would investigate other factors of peroxide's decomposition, like temperature of, light exposed to and pressure of the reacting mixture. These other factors are measurable along an analogue scale and are therefore have findable reaction orders, unlike a catalyst. Furthermore, the experiment procedure created an opportunity for human error, as attaching the rubber stopper to the reacting flask allowed for a random amount of gas to escape the gas cylinder, possibly poisoning the results of the IA. Although I did not find this too prevalent through using averaged values and diligent reaction procedure, it is a risk I would not take again.