How the concentration of an electrolyte affects the rate of production of Hydrogen in alkaline electrolysis.

**RATIONALE**

Eighty-ﬁve percent of the energy consumed globally is provided by fossil fuels, namely coal, oil, and natural gas [1]. Consuming fossil fuels at the rate needed to provide the world with energy produces so much greenhouse gas emissions as a by-product that fossil fuels alone are consider the major contributor to climate change [2]. In this context, hydrogen has been proposed as a promising source of energy for over fifty years [3]. Hydrogen offers several advantages as an energy source: its combustion produces significant energy, water is the only by-product of combustion, and it can be produced from renewable and sustainable sources. In spite of these advantages, hydrogen has failed to be widely used in energy systems due to numerous barriers, including costs of production and storage and the availability of infrastructure [4]

Hydrogen is produced by the electrolysis of water. Water electrolysis involves the decomposition of water molecules (H2O) into hydrogen gas (H2) and oxygen gas (O2) through the application of an electric current.

2 H2O(l) → 2 H2(g) + O2(g)

In a commercial scale of Hydrogen production, the most well-established is alkaline electrolysis, which usually using potassium hydroxide as the electrolyte. In the alkaline electrolysis of water, the following reactions occur:

Reduction (at the cathode) 2 H2O(l) + 2 e- → 2 OH-(aq) + H2(g)

Oxidation (at the anode) 2 OH-(aq) → 2 e- + ½ O2(g) + H2O(l)

As hydroxide ions are the species oxidised, the concentration of hydroxide ions is likely to have a significant influence on the rate of hydrogen production via the alkaline electrolysis method. This investigation will examine the effect of varying the concentration of the alkaline electrolyte on the production of hydrogen via the alkaline hydrolysis method. The effect of electrolyte concentration on the rate will be precisely determined by identifying the reaction order with respect of KOH using natural log analysis of the data.

**RESEARCH QUESTION**

How does changing the concentration of potassium hydroxide electrolyte (0.2M to 1.0M) affect the rate of production of 25 mL of hydrogen gas via alkaline electrolysis?

**Original experiment**

The online simulation ‘Electrolysis Experiments’ (Crowley 2003) examined how changing an electrolyte’s chemical composition can affect the volume of hydrogen gas produced during electrolysis. The two electrolytes examined, acidified water and hydrochloric acid, offered different concentrations of H+(aq) available to undergo reduction. The higher concentrations of H+(aq) in the Hydrochloric acid did produce significantly higher amounts of hydrogen gas.

**Modifications to the methodology**

The original experiment was modified by extensions including:

* changing to an alkaline electrolysis using KOH as an electrolyte with silver electrodes. This allowed the change in the independent variable - to concentration of KOH (not [H+]).
* timing the electrolysis. This allowed the rate of production of Hydrogen (dependent variable) to be calculated.
* five concentrations of KOH (0.2 M, 0.4 M, 0.6 M, 0.8 M and 1.0 M) were used. This should be sufficient variation in the independent variable to accurately identify a trend in the electrolyte effect. Each concentration was trialled three times. This should be sufficient to reduce uncertainty for the dependent variable.

The original experiment was refined by modifications including:

* + reducing the amount of hydrogen collect to a volume of 25 mL. This reduced the time needed for the trials.
	+ using a 25.00 ± 0.25 mL measuring cylinder rather than a test tube (Figure 1) to quantify the volume of hydrogen gas produced (controlled variable)

**RISK MANAGEMENT**

Table 1: Assessment of risks

|  |  |  |  |
| --- | --- | --- | --- |
| **Source of Risk** | **Risk** | **Mitigation of risk** | **Response to occurance** |
| **Chemical**: Potassium hydroxide electrolyte exposure to eyes and skin (irritant, but not corrosive) | Medium | Appropriate PPE will be worn, including safety glasses and a lab coat. | If exposure to eyes occurs, the eye wash will be used to irrigate eyes. If skin exposure occurs, the area will be rinsed completely with water. Inform the teacher. |
| **Chemical**: Possible combustion of Hydrogen or Oxygen gas when collected | Slight | No flame sources will be used. Electrical contacts will not be manipulated until gas is released. Safety glasses worn.  | Assess for physical injury and treat appropriately. Assess equipment for damage and replace if necessary. Inform the teacher |
| **Environmental:** Disposal of Potassium Hydroxide electrolyte (avoiding local waterway contamination) | Slight | The electrolyte used in the investigation (and any excess) will be collected, returned to the prep romm for storage and appropriate disposal.  | Nil |
| **Ethical:** No ethical concerns are associated with this investigation |

**Analysis**

**Raw data**

Table 2: Concentration of electrolyte and time for production of 25mL of hydrogen

|  |  |
| --- | --- |
| **Concentration of KOH(aq)** (mol/L) | **Time** (seconds) |
| **Trial 1** | **Trial 2** | **Trial 3** |
| 0.2 | 359.5 | 368.5 | 364.5 |
| 0.4 | 360.0 | 345.5 | 327.5 |
| 0.6 | 325.5 | 339.5 | 333.5 |
| 0.8 | 343.5 | 307.0 | 327.5 |
| 1.0 | 307.0 | 339.5 | 326.5 |

\*Operating temperature of the apparatus = 26.0 °C = 299.0 K

\*Pressure in the lab = 101 kPa

\*Uncertainty in time = ± 0.5 seconds

\*Uncertainty in 25 mL volume = ± 0.5 mL

**Processing of data**

Table 3: Calculations for secondary data – trials at 1.0M used

|  |  |  |
| --- | --- | --- |
| Explanation | Formula used to process data | Sample calculations for 1.0 M KOH |
| Calculation of average time for 25 mL of gas |  |  |
|  | \**\*Comparison of random and measurement uncertainty means random uncertainty will be used to represent uncertainty for time in the investigation.* |
| Calculation of moles of Hydrogen in 25 mL of gas |  | *mL* (sig fig continued) |
|  |  *moles* |
| *(note all other values in n calculation are “known” values)* | *moles* *moles* |
| Rate of hydrogen production |  | *moles/s* *moles/s* |
|  |  |
| Natural log of rate and [KOH] |  |  |

Table 4: Concentration of KOH and the rate of electrolysis.

|  |  |  |
| --- | --- | --- |
| Concentration of KOH(aq) (mol/L) | Rate of H2 production (moles/s) | Uncertainty in rate of H2 production (moles/s) |
| 0.2 | 2.46 x 10-6 | 3.24% |
| 0.4 | 2.60 x 10-6 | 6.72% |
| 0.6 | 2.69 x 10-6 | 4.10% |
| 0.8 | 2.74 x 10-6 | 7.60% |
| 1 | 2.76 x 10-6 | 7.01% |

Figure 1: Rate of Electrolysis

Figure 2: Natural log graph of [KOH] and Rate

**Identification of trends and relationships**

As the concentration of the Potassium hydroxide electrolyte in the alkaline electrolysis cell increased, the rate of production of Hydrogen gas increased. At the lowest concentration of 0.2 M the rate of production was 2.46 x 10-6 moles/L, and at the maximum concentration of 1.0 M, the rate was 2.76 x 10-6 moles/L. The relationship was non-linear, with smaller increases in the rate as concentration increased, and is best described by a power equation (with an R2 of 0.99):

Rate of H2 production = 3 x 10-6 x conc**0.0748**

This relationship suggests that the change in concentration of KOH did not have a significant effect on the rate of production. An increase of five-fold in the concentration resulted in an increase of 1.12 fold in the rate. The natural log graph indicates that the reaction order with respect to [KOH] is 0.075. Given that reaction orders are generally multiples of 0.5, and an average uncertainty in the rate of 6%, the value of 0.075 may effectively be zero. This suggests that the concentration of KOH has little to no influence on the rate of Hydrogen production.

**Identification of Uncertainty**

There is significant uncertainty in the data. The rate of H2 production had an average uncertainty of under 6%, with higher uncertainty (~7%) at higher rates, and the highest uncertainty being 7.6%. These values are not high and should reflect a degree of certainty about the data. However, the rate values are very close to each other (12% range), and values for rate do not differ by very much more than the uncertainty range (± 6%). This is most clearly shown in figure 1, where the rate values almost all lie within the uncertainty ranges of the other values. Therefore, despite a relatively low calculated uncertainty, and a trend line which appears to accurately describe a trend in the data (R2=0.99), the trend contains a significant degree of uncertainty.

**identification of limitations**

Several limitations appear within the methodology. Given the uncertainty was found to be relatively high, there should have been more than three trials for each concentration. This may have reduced the uncertainty to a point where the trend may have been conclusively identified. The concentration of KOH used was not reflective of commercial operating concentration which are approximately four to five moles/L. This was a known limitation as concentrations of KOH within a commercial range are considered quite caustic, and significant additional safety procedures would have been needed. Therefore, the trend identified may be limited by not be representative of higher concentrations.

**Interpretation and Evaluation**

**conclusion**

The concentration of potassium hydroxide does not significantly affect the rate of hydrogen gas production in alkaline electrolysis. The relationship between concentration and rate was determined to be

Rate of H2 production = 3 x 10-6 x conc**0.0748**

This relationship showed that a 500% increase in the concentration resulted in only a 12% increase in the rate. The reaction order with respect to KOH was close to, and probably equal to zero. It therefore appears that significantly increasing the concentration of potassium hydroxide in alkaline electrolysis should not be considered as an economical method for improving the production of hydrogen gas.

**evaluation of reliability**

The data recorded and thus the existing methodology would generally be considered reliable considering the relatively low relative uncertainty (average <6%) in the data. However, the variation in the measured rates was very small, and were determined to be well within the ranges of the uncertainties. Therefore, these rate values cannot be considered reliable. It was further identified that the trend could vary significantly and still fit within the range of uncertainties, and therefore the determined relationship between concentration and rate was also considered unreliable. Conversely, the rate values varied so little that the conclusion that concentration of KOH does not significantly affect the rate of hydrogen gas production is considered highly reliable.

**evaluation of validity**

The main conclusion that concentration of the electrolyte does not significantly affect the rate of H2 production is likely to be valid. The very small variation in the rate vales contrasted greatly with the significant variations in the concentration, and strongly suggests that for the concentration used in this experiment, there was little to no variation in the rate of H2 production.

However, there were two limitations which did significantly affected the validity of the results. The use of non-commercial concentrations of the electrolyte means the conclusion reached may not be valid within commercial electrolysis situations. The relative uncertainty in the rate and the very small variation in the rate values mean that other uncontrolled factors may have influence the determination of the rate values more than the concentration of KOH. This suggests that the specific mathematical relationship between concentration and rate determined by the investigation is also not valid.

**improvements and extensions**

The methodology of this investigation would be improved by doing more than three trials at each concentration. This would reduce the random uncertainty and improve the reliability of the data. Additionally, the concentration of the electrolyte should be varied safely beyond 1.0 M with more than five variations. This would reduce the uncertainty in the trend, and improve the validity of the conclusion as it relates to commercial applications.

This investigation could be extended by investigating other factors which affect rate, specifically temperature of the electrolyte solution. This would enable a more comprehensive picture of the factors which affect the rate of hydrogen production in alkaline electrolysis.

1. Tverberg G. BP data suggests we are reaching peak energy demand. 2015. Available from: https://ourﬁniteworld.com/2015/06/23/bp-data-suggests-we-are-reaching-peak-energy-demand [Accessed: July 8th, 2023]
2. United Nations – Causes and Effects of Climate Change. https://www.un.org/en/climatechange/science/causes-effects-climate- change#:~:text=Fossil%20fuels%20%E2%80%93%20coal%2C%20oil%20and,of%20all% 20carbon%20dioxide%20emissions. [Accessed July 8th, 2023]
3. Winsche WE, Ho􀀁man KC, Salzano FJ. Hydrogen: Its Future Role in the Nation’s Energy Economy. Science. 1973; 180: 1325
4. Hanley ES, Deane J, Gallachóir BÓ. The role of hydrogen in low carbon energy futures—A review of existing perspectives. Renewable and Sustainable Energy Reviews. 2018; 82: 3027-3045