

UNIVERSITY OF GHANA

Optimization of Some Influence Factors in the Electrolytic Production of Sodium Hydroxide

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By

AGYEMANG WIREDU MARK

(10301889)

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**MPHIL NUCLEAR TECHNOLOGY APPLICATIONS IN PETROLEUM AND
MINING INDUSTRIES**

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DECLARATION

I, AGYEMANG WIREDU MARK, the under signed, hereby declare that this thesis is my own work and to the best of my knowledge it has never been submitted for the award of a degree in any university. All sources of information used in this work have been duly cited and acknowledged.

.....
AGYEMANG WIREDU MARK

DATE:

.....
DR. ANDREW NYAMFUL

(PRINCIPAL SUPERVISOR)

.....
DR. K.A. DANSO

(CO-SUPERVISOR)

DATE:

DATE:

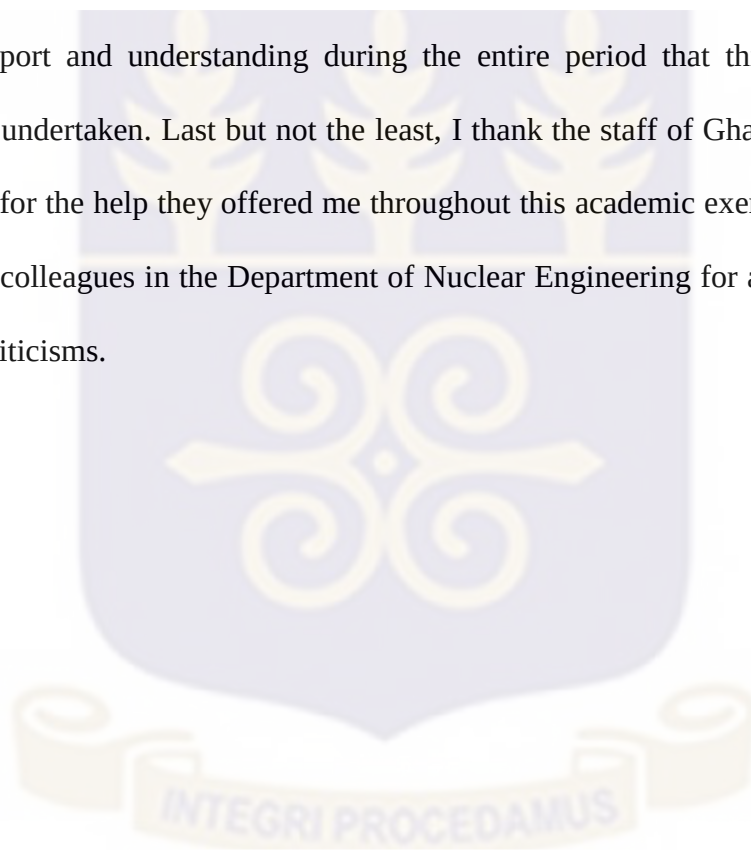
DEDICATION

Nothing is impossible with God and to my dearest brother Dr. Michael Agyemang-Wiredu, you are God sent and a lovely brother. Finally, I would like to thank my wonderful sisters and brothers Ewurama Darkoa, Marian Wiredu, Isaac Wiredu and my lovely twin brothers Sampson and Samuel Asante for their support and endless encouragement throughout this process. God bless you all.



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ABSTRACT

Sodium hydroxide is one of the most important chemicals in the global chemical trade. It is the main feedstock used in the manufacture of many products used in everyday life. The production of sodium hydroxide in a country is a measure of the development of its chemical industry. In this study, some factors that influence production of NaOH from NaCl using electrolytic cell were optimized. The optimum conditions for the production of NaOH were found to be 50° SAL brine strength, 6.0cm electrode gap, 5 electrodes in both anode and cathode compartments and 80V. The pH of the catholyte obtained at the optimum conditions was 13.88 at 360.3K, 2 hours and 5.40A.



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LIST OF ACRONYMS

DSA	Dimensionally Stable Anodes
ODC	Oxygen Depolarised Cathode
WEO	World Energy Outlook



CHAPTER ONE

INTRODUCTION

This chapter outlines the role of sodium hydroxide in the chemical and alkaline fuel cell industry. It also delineates the objectives and justification of the research.

1.1 Background of the study

Due to rapid industrial and population growth, the energy demand worldwide is increasing daily. According to IEA World Energy Outlook, the global population is expected to increase by 30% the next 25 years, where 80-90% of the increase is expected to be in developing countries (Singh et al., 2012). Fossil fuels provide 81% of the world's commercial energy supply (OECD, 2009). Although fossil fuels play a crucial role in the world energy market (Goldemberg, 2006), they are finite and non-renewable on a human scale and are limited physically and more stringently economically (Perez et al., 2014). The reserves of these conventional energy sources particularly oil, natural gas and coal are not only non-renewable but they are also depleting rapidly (Rabbani et al., 2014). Moreover, the main environmental challenge in our time is to avoid or reduce the impacts of global warming. Carbon dioxide is the main greenhouse gas and 70-75% of all carbon dioxide emissions is due to combustion of fossil fuels (Halvorsen et al., 1989). The total carbon dioxide produced as a result of combustion of fossil fuels since the beginning of the industrial revolution actually exceeds the observed increase in the atmosphere (Boden et al., 2009). There is a narrow window of time left to begin the long process of stabilizing greenhouse gas concentrations at a level that can avert devastating and irreversible impacts from climate change (O'Niell et al., 2002). According to world energy outlook (WEO) 2007, there is worldwide research into other reliable energy resources to replace fossil fuels and this is mainly due to the uncertainty surrounding the future supply of fossil fuels as well as

the carbon dioxide emissions resulting from combustion of fossil fuels. For example US Department of Energy has proposed a transition plan from an oil based economy to a hydrogen economy by 2040. Germany has planned to obtain all required energy from hydro and renewables. Canada is heavily investing in renewables and offering different incentives to domestic and industrial users who are partially or fully meeting their energy demands by renewable energy (Rabbani et al., 2014). Fuel cell can provide clean energy and reduce the energy supply demand gap (Daghe et al., 2017). The use of fuel cells in both stationary and mobile power applications can offer significant advantages for sustainable energy (Alhassan et al., 2006). Also, by integrating the application of fuel cells in connection with renewable energy storage and production methods, sustainable energy requirement may be achieved (Melean, 2001). The fuel cell (for example oxy-hydrogen generator) technology has also proven its technical viability in several domains of application such as backup power generation and vehicle propulsion (Garche et al., 2015). Oxy-hydrogen is an enriched mixture of hydrogen and oxygen bonded together molecularly and magnetically (Brown, 1978). Since the oxy-hydrogen generator (alkaline fuel cell) uses sodium hydroxide solution as catalyst in its operation, the influencing factors affecting the yield of sodium hydroxide need to be investigated.

Sodium hydroxide is among the top 10 chemicals manufactured in the world, and is involved in the production of several products that are used in everyday life (O'Brien et al., 2005). Sodium hydroxide is among two primary elements of 60 % of Europe's chemical industry production (Siracusano et al., 2010). It is used in chemical industries and for manufacture of products such as glass, textiles, soap, detergents, paints, and ceramics (Saksono et al., 2013) and most importantly, as fuel supplement in alkaline fuel cells. It has also found applications in ovonic renewable hydrogen process for reformation of organic matter (Reichman et al., 2010) and also in hydrothermal gasification of glucose and other biomass

to produce hydrogen gas (Onwudili et al., 2009). It is also used together with steam to pyrolyze dechlorinated PVC and activated carbon to generate sodium carbonate (Kamo et al., 2006).

Knowledge of the influencing factors in electrolysis of brine is vital for improving the performance of electrolytic cells (Domga et al., 2016) for sodium hydroxide production. In this present work, electrolytic cell was designed and used to study the most important factors such as brine strength, gap between electrodes, number of electrodes and voltage and to investigate their effect on maximization of sodium hydroxide production.

1.2 Statement of the problem

The consumption of fossil fuels spawns environmental considerations in addition to issues of energy demand and resource availability (Perez et al., 2014). At the global level, scientists warn that the combustion of fossil fuels is significantly changing the world's climate system. In order to overcome the draw backs of the fossil fuels, it is the time to replace fossil fuels with electrolyte such as sodium hydroxide and be used in HHO generator to run engines etc. The performance of the HHO generator is based solely on the catalytic efficiency of the electrolyte material used; it has become more vital to investigate design parameters which could best be suitable in producing quality electrolyte from cheap alternative sources.

1.3 Justification

With the increasing demand for energy worldwide, an appropriate technology which could give an unlimited supply of energy and at the same time not undermining the safety of the environment must be sort after. The brown gas (oxy hydrogen) has by far proved to be suitable in replacing the diminishing fossil fuels. The performance of the oxy hydrogen

generator rests solely on the catalytic efficiency of the electrolyte material (sodium hydroxide) used in its operation; it has therefore become more imperative that the engineering parameters influencing the yield of sodium hydroxide be investigated.

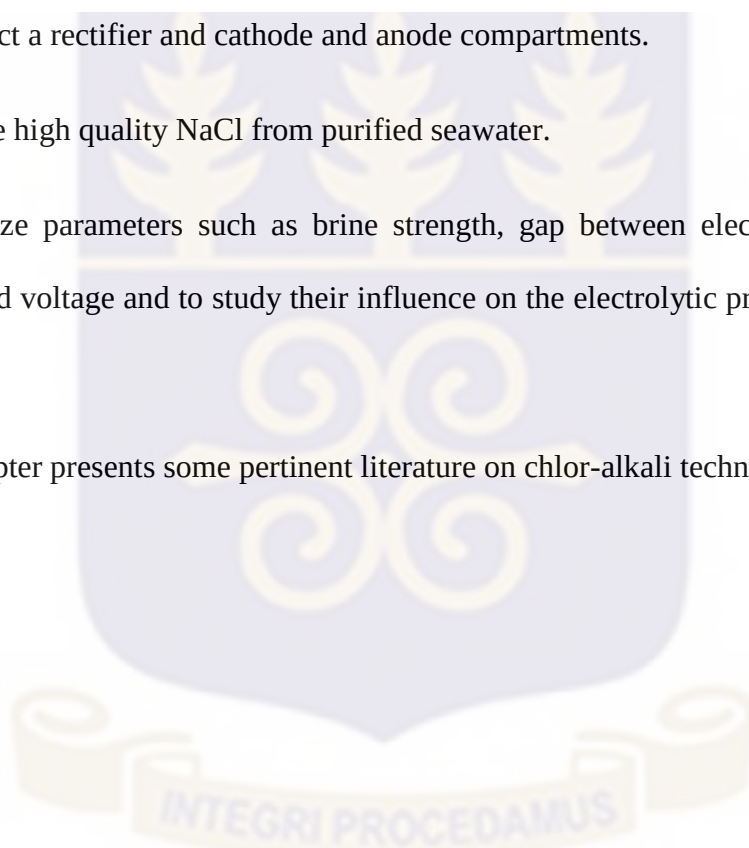
1.4 Main objective

To construct an electrolytic cell and then using it to produce NaOH from purified saltbrine.

The specific objectives are

1. To construct a rectifier and cathode and anode compartments.
2. To produce high quality NaCl from purified seawater.
3. To optimize parameters such as brine strength, gap between electrodes, number of electrodes and voltage and to study their influence on the electrolytic production of NaOH from NaCl.

The next chapter presents some pertinent literature on chlor-alkali technologies.



CHAPTER TWO

LITERATURE REVIEW

This chapter describes the various technologies used in chlor-alkali production. It also outlines some recent improvements in the chlor-alkali industry.

2.1 Introduction

Sodium hydroxide is produced by electrolysis process. Electrolysis is a process whereby the bonds in a compound are separated by passing an electric current through it (Saksono et al., 2013). Sodium hydroxide is produced in an electrolytic cell (Domga et al., 2016). The electrolytic cell (Figure 2.1) is a vessel filled with electrolytes (which are separated by an ion exchange membrane) in which the electrodes are immersed and connected electrically to a power supply (Cardarelli et al., 2008).

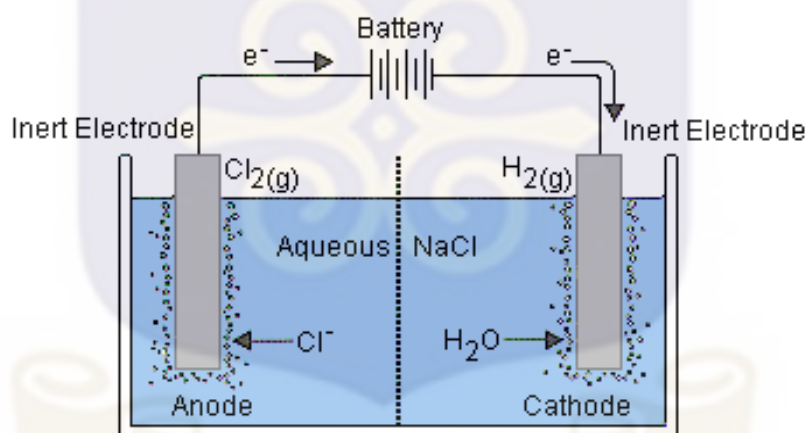
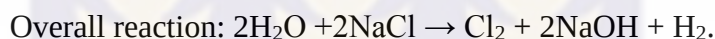
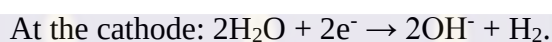


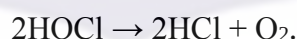
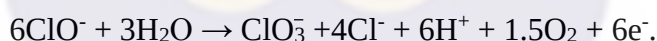
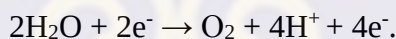
Figure 2. 1: Diagram of an electrolytic cell.

During electrolysis of brine, NaCl is dissociated in the solvent and forms ions (Na^+ and Cl^- ions) in solution. The positive electrode is called anode and negative electrode is called cathode. Each electrode attracts ions which have opposite charges so that ions with negative charges are attracted to the anode compartment and ions with positive charges are attracted to the cathode compartment (Saksono et al., 2013). Chloride ions (Cl^-) which are discharged

at the anode compartment, are oxidised to chlorine gas at the anode compartment. Hydrogen ions (H^+) produced at the cathode compartment, are reduced to hydrogen gas at the cathode compartment. Sodium ions (Na^+) discharged at the anode compartment, migrate to the cathode compartment and combine with hydroxyl ions (OH^-) to form sodium hydroxide in the cathode compartment (Domga et al., 2013). The overall reaction taking place in the electrolytic cell proceeds through the following reactions:



One challenge in the overall reaction is the evolution of oxygen gas (Hansen et al., 2010) which occurs due to direct anodic oxidation, chlorate formation and lastly decomposition of hypochlorite which compete with the reaction leading to the formation of chlorine gas and this eventually results in lowering the current efficiency from 1-5% (Domga et al., 2016).



Usually selective electrodes and anolyte acidification are measures used to reduce the oxygen side reaction to allow a current efficiency of about 99% (Karlsson et al., 2015). In order to increase the current efficiency (by reducing the oxygen side reactions) in the electrolytic production of sodium hydroxide, all modern cells since the 1970's use Dimensionally Stable Anodes (DSA). The DSA is an industrial electrode which is made of RuO_2 as an active component (Chandler et al., 1997), inert oxide such as TiO_2 as stabilizer and coated onto titanium substrate (Malpas et al., 2006). The main processes used for

production of sodium hydroxide are diaphragm, mercury and membrane cell electrolysis. The difference in these cells lies in the manner in which the sodium hydroxide and chlorine gas are prevented from missing with each other in order to obtain pure products (Domga et al., 2016). The metal used as cathode is steel in the case of a diaphragm cell, nickel in membrane cell and mercury in mercury cell (Siracusano et al., 2010). In the membrane cell, there are two types of electrolyzers namely monopolar and bipolar. In the monopolar type, the anode and cathode are arranged electrically in parallel whereas in the bipolar the cathode of a cell is connected to the anode of an adjoining cell, so that the cells are in series and each electrolyzer has its merits and demerits (Zeng et al., 2010). Despite being an old technology, the membrane process is influenced by membrane suppliers (Ana, 2005). The main problem associated with these three processes is the high consumption of electrical energy which usually represents a substantial part of the production cost (Stantorelli et al., 2009). Also, there are only five major suppliers of cell technology and they are: Asahi Kasei Corporation, Chlorine Engineers, Eltech Systems Corporation, INEOS Chlor and Uhde (O'Brien et al., 2005).

2.2 The Membrane Cell

Due to incidents of mercury poisoning in Minamata and Niigata in 1972, many countries for example Japan started switching to membrane cells and today has no more mercury cells in operation (O'Brien et al., 2005). The power consumption in the membrane cell is the lowest compared to the three technologies (Wiberg, 2001). However, certain industries such as the rayon industry consider the sodium hydroxide quality from membrane cells to be slightly inferior to that produced via the mercury cell method due to the higher chloride and chlorate content. The key principle of the membrane process is the selective permeability of the membrane. The membrane allows only specific components to permeate through it

(Lakshmanan et al., 2013). The actual transport processes occurring within the membrane are yet to be understood fully (Grotheer et al., 2006). Research is on-going in an effort to better understand how these membranes work so as to tailor make membranes with highly selective permeability and exhibiting low electrical resistance (Grotheer et al., 2006). The ion exchange membrane separates the cathode side from the anode side. The membrane currently used in industry is comprised of two layers to be able to withstand the significantly different conditions on either side of it. The two layers are made of per fluoro sulphonic acid and per fluoro carboxylic acid films (Lakshmanan et al., 2013). A saturated brine solution that has been purified is channeled to the anode compartment while demineralized water is fed to the cathode compartment. During the electrolysis, sodium ions and some water permeates through the membrane and enter the cathode compartment. Chlorine gas is formed in the anode compartment. In the cathode compartment, water molecules are electrolyzed and release hydrogen gas. The hydroxyl ions combine with the sodium ions that permeate through the membrane to form sodium hydroxide. The depleted brine that leaves the anode compartment is sent for processing and re-concentration before it is fed back to the anode compartment. In the cathode compartment, only 32% of the sodium hydroxide concentration is taken out for further processing, while demineralized water is continuously fed to the cathode compartment to maintain the sodium hydroxide concentration in the compartment at 30%. Based on current technology, the highest sodium hydroxide concentration that can be produced in the membrane electrolyser is 35% (Moorhouse 2001).

2.2.1 Recent Advances in the Membrane Cell Process

Several developments have come into play to enhance the membrane cell process. For example Dupont developed N2030/NE2040 membranes which exhibit lower voltage drop.

Akzo Nobel developed a nano-filtration method for removing sulphates from brine prior to electrolysis. Lanxess developed new smaller resins with greater adsorption capacity, extending resin on-line time by 50-100%. Uhdenora reduced power consumption in the electrolyser from 2130 kWhr/t in 2004 to 2035 kWhr/t in 2012 via version 6 BM2.7 electrolyser. Uhdenora again teamed up with Bayer to develop and test the NaCl-ODC with significant power reduction of 25% (Lakshmanan et al., 2013). One of the significant developments in the chlor-alkali industry is the oxygen-depolarized cathode (ODC) process in which oxygen is introduced into the electrolysis chamber via a porous cathode. This process yields a significant reduction in electrical power consumption of 30%, with hydrogen no longer evolved from the cathode. Instead of hydrogen, oxygen is released from the cathode of ODC cells (Kiros et al., 2008). Initial studies indicate that the existing membrane plants cannot be modified to the ODC process due to differences in operating conditions and use of the special cathodes (Chlistunoff, 2005). A demonstration electrolyzer with a capacity of 20,000 tons per annum of chlorine has been operational for Bayer at its site in Uerdingen since May 2011. Research work is ongoing to determine types of electrode coatings to be used (Moussallem et al., 2012). The ODC process has also been put to commercial use for electrolysis of HCl to produce chlorine, with significant savings in electrical costs. Here too, oxygen is introduced at the cathode and no hydrogen is evolved. This is a significant development given that in most synthesis reactions using chlorine, one major by-product is hydrochloric acid. The use of the ODC process helps recover chlorine from HCl.

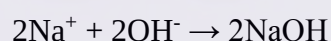
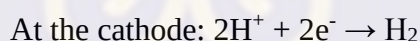
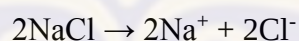
2.2.2 Comparison of the Membrane Cell Process, the Diaphragm Cell and Mercury Cell

There are distinct advantages in using the membrane cell technology. The polluting nature and environmental concerns associated with the other technologies, has resulted in all new chlor-alkali plants being built to be of the membrane cell process (Lakshmanan et al., 2013). The membrane cell does not use harmful substances such as mercury or asbestos and hence there can be no potential release of these materials into the product or the environment. However, higher quality of salt and brine are required in the membrane process which results in higher cost. The membrane cell consumes less electrical power compared to mercury and diaphragm cells. The sodium hydroxide produced in the membrane cell may contain higher chlorate levels than in the mercury and diaphragm cell process. Also, the production of per fluoro carboxylic acid and per fluoro sulphonic acid in the membranes do result in the release of pollutants (Karrman et al., 2010).

2.3 The Diaphragm Cell

It was in 1851 that the combined processing of sodium hydroxide and chlorine came about in what is today known as the diaphragm cell process. The Griesham diaphragm cell went into operation in Germany in 1890 (Schneiders et al., 2001). The diaphragm cell underwent continuous improvements until 1920 when asbestos became the major material used for the diaphragm and remained the major material used for the following 80 years (O'Brien et al., 2005). In the diaphragm cell process, asbestos were used to separate the sodium hydroxide from the chlorine (Euro Chlor, 2007). The diaphragm cell produced sodium hydroxide solution of around 12%, but its major drawback was the high salt content (Lakshmanan et al., 2013) in its sodium hydroxide. Platinum or magnetite were the early material used for the anodes of the diaphragm cells. However due to cost considerations as well as limitation

on the current density when using magnetite, graphite became the major anode material until the 1970's. It was in the 1970's that a titanium base coated with a catalytic layer comprising of mixed oxides was developed (Lakshmanan et al., 2013). They were successfully used with long life and low cell voltage. These anodes became known as Dimensionally Stable Anodes and were used by all the technology suppliers (Lakshmanan et al., 2013). There were developments made to improve the asbestos diaphragms such as mixing asbestos with polytetrafluoroethylene which produced a dimensionally stable diaphragm (O'Brien et al., 2005). Then came a stabilized diaphragm, which had a polymer added into the asbestos slurry, and produced a diaphragm that did not swell (IPPC, 2001). This was followed by the development of bipolar diaphragm cells with one side as the anode and the other side as the cathode (Lakshmanan et al., 2013). They were assembled together into a cell and tightened in place with tie rods which made them appear to look like plate and frame filter presses. The reactions occurring in the diaphragm cell are as follows:

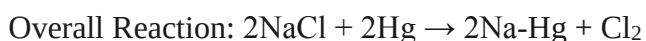
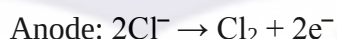


As the sodium hydroxide concentration increases at the anode, there is a greater likelihood for it to be discharged into oxygen and water (Wiberg, 2001). For this reason, diaphragm grade sodium hydroxide is only produced around 12-15% concentration in the electrolytic cell. The height of brine in the anode compartment is maintained above the level in the cathode side to enable brine to slowly permeate through the diaphragm (Varjian, 2003). Saturated brine is fed to the anode compartment, where electrolysis of the brine takes place. Chlorine is formed at the anode. While sodium ions travel through the diaphragm, some sodium chloride are also transported along with it. At the cathode, hydrogen gas is formed

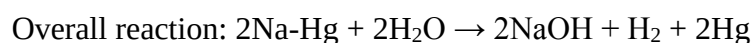
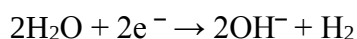
and the weak sodium hydroxide containing around 14% sodium chloride is sent for further processing. The solution is then channeled through three or four evaporation processes to achieve a concentration of 50% (Lakshmanan et al., 2013). The salt crystallizes out on saturation of the sodium hydroxide and it is separated from it via crystallization and filtration and reused in the process. The quality of the sodium hydroxide from diaphragm cells is considered to be low due to its high salt content of up to 1.3% and high sodium chlorate content of 0.3% with other impurities also at levels exceeding that from the other electrochemical processes (Lakshmanan et al., 2013). The sodium hydroxide produced from the diaphragm cell is also known as diaphragm cell grade and finds application in industries without stringent quality requirements.

2.4 Mercury Cell

The Castner-Kellner mercury cell went into operation in 1892 (IPPC, 2011). The process within a mercury cell differs somewhat from that in a diaphragm cell. The mercury cell is composed of an electrolyzer and a denuder or sometimes called a decomposer (O'Brien et al., 2005). The reactions in the electrolyzer are as follows:



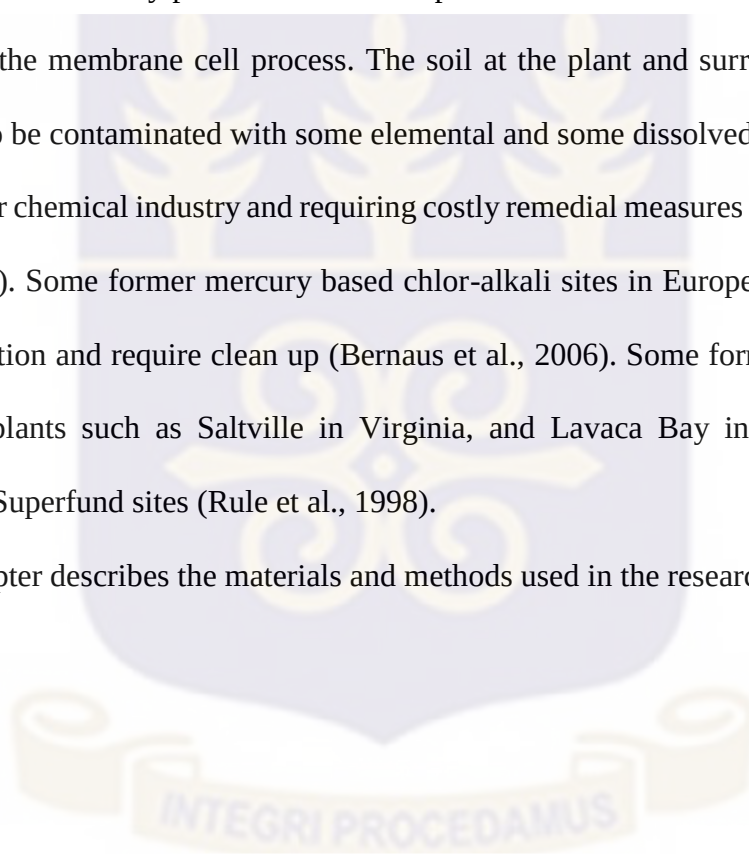
Mercury acts as the cathode in this reaction and also forms an amalgam with sodium. Mercury is not consumed in the process. This amalgam is reacted with water in the denuder to produce sodium hydroxide at the desired concentration. That sodium hydroxide of 50% concentration can be produced directly from the denuder, without any need for further concentrating it (Euro Chlor, 1998). In the denuder the following reactions occur:



At the outlet of the decomposer, the sodium hydroxide which is at 50% strength does not require further processing. The mercury cell process is known to produce the highest quality caustic soda, but its major drawback is that its products has some mercury present (Wiberg 2001). Mercury levels are typically below 1ppm while sodium chloride content is typically below 10ppm, and sodium chlorate content is below 1ppm. The sodium hydroxide produced from this process is referred to as Mercury Cell Grade or Rayon Grade. This is because the production of rayon prefers sodium hydroxide such as that produced via the mercury cell process (O'Brien et al., 2005). Due to its polluting nature and the move away from mercury, there are no more new mercury cells being installed in the world. There are still a few old mercury cell units operating, but due to calls for greener technologies, their days are numbered. Diaphragm technology made up 15% of the capacity, with 39% coming from membrane technology. As at the end of 2011, mercury process has dropped to 31%, diaphragm process to 13% and the membrane process has increased to 52% (IPPC, 2011). Globally, the number of mercury process plants have reduced from 92 plants in 2002 with a capacity of 9million mt/yr down to 57 plants in 2010 with 5.5million mt/yr capacity (Euro Chlor, 2011). There is a voluntary commitment to phase out the use of the mercury cell process by 2020 by European manufacturers (Euro Chlor, 2012). The chlor-alkali industry claims that the levels of mercury from sodium hydroxide manufacture have reduced substantially over the years, and that the industry is now a minor contributor to environmental mercury levels (Singh, 2010). One of the points of concern from mercury cells is the residual levels of mercury (typically 0.5ppm and below) present in products from the cell (Dufault et al., 2009) and the use of mercury containing chemicals for potential

microbial action that converts mercury to methyl mercury which is highly toxic (Gochfeld, 2003). Other disadvantages of the mercury cell process are the potential hazards from exposure to mercury and mercury vapours which are a known neurotoxin. They also require larger floor space than diaphragm cells and membrane cells and consume more energy for the production of chlor alkali products (Lakshmanan et al., 2013). Some former mercury process chlor-alkali plant sites show signs of soil contamination with mercury. A lot of work are required to remove the mercury from such soils. One such site is in Botany, Australia which operated a mercury process chlor-alkali plant on that site from 1944 to 2002 before switching to the membrane cell process. The soil at the plant and surrounding sites have been found to be contaminated with some elemental and some dissolved mercury leaving a bad legacy for chemical industry and requiring costly remedial measures (Golder Associates Pty Ltd 2012). Some former mercury based chlor-alkali sites in Europe have shown signs of contamination and require clean up (Bernaus et al., 2006). Some former mercury based chlor-alkali plants such as Saltville in Virginia, and Lavaca Bay in Texas have been classified as Superfund sites (Rule et al., 1998).

The next chapter describes the materials and methods used in the research.



CHAPTER THREE

MATERIALS AND METHODS

This chapter presents materials and methods used in this work.

3.1 Descriptive Features of the Salt Refining Plant.

The salt refining plant (Model number GYSR-2000, made by Shanghai Genyond Technology Co., Ltd in China) consists of a feed hopper (Fig.3.1.1) in which salt of volume of about 3m³ is fed manually using a shovel.



Figure 3.1. 1: A feed hopper for salt collection.

The feed hopper has a rectangular shape and made of stainless steel with length 65.0cm, breadth 40.0 cm and height 18.0cm and contains a grate that has a rectangular shape of length 20.0cm, breadth 15.0cm and height 10.0cm that separates (through agitation of a vibrator) the smaller salt crystals (0.1 - 0.2mm) from the bigger ones (0.25 – 0.40mm) into a rectangular stainless steel container of length 250.0cm, breadth 125.0cm and height 85.0cm (Fig.3.1.2).



Figure 3.1. 2: A stainless steel container for receiving salt from feed hopper.

The salt collected in the stainless steel container (upgraded salt) is transferred through a screw conveyor (Fig.3.1.3) into a washer and classifier equipment.



Figure 3.1. 3: A screw conveyor for transporting salt into the washer.

The washer and classifier equipment are made of stainless steel. The washer has valves and nozzles for adjusting the brine flow rate as well as the direction of the salt slurry. The classifier equipment is rectangular in shape and has length 15.0 cm, breadth 9.5 cm and height 6.5 cm. The classifier has a sieve embedded in it and it separates the salt particles according to their sizes by agitation. From the washer and the classifier, the salt slurry goes into a centrifuge cell for the salt and other unwanted solid substances to be separated. A

filtrating pump (Fig.3.1.4) transfers the separated salt obtained from the centrifuge cell (Fig.3.1.5) into another classifier made of the same material and same dimensions as described earlier.



Figure 3.1. 4: A filtrating pump for transferring separated salt from the centrifuge cell into a classifier.



Figure 3.1. 5: A centrifuge cell for separating salt in the slurry from unwanted particles.

In the classifier, there are sets of valve for adjusting the brine flow rate. From the classifier, the salt moves into a salt dryer for drying through heating; and salt crystals formed, are reduced to desired particle sizes in a grinding mill.



Figure 3.1. 6: A dryer for drying the refined salt (it has heat exchange column).



Figure 3.1. 7: Silo for storing NaCl.

3.2 Electrolytic Cell Setup

The anode compartment comprised a brine solution in a cylindrical plastic container of height 18.5cm and diameter 7.0cm in which stood a cylindrical graphite rod (as electrode) of length 30.0cm and diameter 1.0 cm held vertically through a 1.1cm diameter hole made in a circular aluminium plate of diameter 12.5cm and thickness 1.0cm placed on top of the cylindrical plastic container. The cathode compartment comprised distilled water in a cylindrical plastic container in which stood a cylindrical graphite rod (as electrode) of length 30.0cm and diameter 1.0cm held vertically through a 1.1cm diameter hole made in a circular

aluminium plate of dimensions as described in the case of the anode. The cylindrical plastic containers of the two compartments was placed on a horizontal plane surface and were connected by a salt bridge. The salt bridge was placed horizontally at a distance 4.5cm vertically down from the top of any of the cylinders. The salt bridge was made of Perspex glass of bore diameter 1.0cm and length 6.0cm and had been impregnated with an absorbent cotton wool that had been dipped in the brine solution. The electrode in the anode compartment was connected to the positive terminal of a rectifier. Similarly, the electrode in the cathode compartment also connected to the negative terminal of the rectifier using 16.0mm flexible copper wires. The voltage range of the rectifier was between 0 and 400V inclusive.



Figure 3.2. 1: Graphite electrodes electroplated with copper.

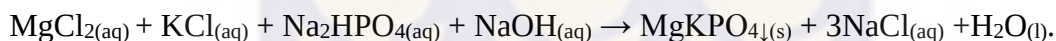
The graphite electrodes were manufactured by Qingdao Tennry Carbon Co., Ltd, professional manufacturer of graphite products in Shandong Province in China.

3.3 Purification of Seawater

3.3.1 Removal of Mg^{2+} , K^+ and SO_4^{2-} ions from Seawater by Precipitation Method

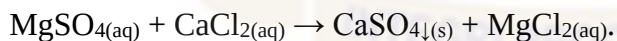
3.3.2 Removal of Mg^{2+} and K^+ ions

8 cm³ of 15 %w Na_2HPO_4 solution were added to 1000 cm³ of seawater of pH 7.0 (obtained from Pambros Salt Industry at Weija, Accra) being stirred at 100rpm. The pH of the mixture was adjusted to 9.0 using 2N NaOH solution. After 4 minutes, 2 cm³ of the 15 %w Na_2HPO_4 solution were added gradually to the mixture and the pH of the mixture adjusted to 9.0 as described earlier. This process was repeated every 4 minutes till total volume of 15 %w Na_2HPO_4 solution added was 16 cm³ maintaining the pH of the mixture at 9.0.



3.3.3 Removal of SO_4^{2-} ions

10 cm³ of 15% w CaCl_2 solution were added to the mixture obtained in 3.3.2 above and the pH of the mixture adjusted to 9.0 using 2N NaOH solution. After 4 minutes, 5 cm³ of 15% w CaCl_2 solution were added steadily to the mixture and the pH of the mixture adjusted to 9.0. This process was repeated every 4 minutes till total volume of 15% w CaCl_2 solution added was 30 cm³ maintaining the pH of the mixture at 9.0.



3.3.4 Filtration of the Precipitated Salts from the Seawater

The mixture obtained in 3.3.3 above was filtered and the residue was air dried to constant weight. The dried residue was subjected to EDAX analysis to determine percentage of Mg^{2+} ,

K^+ and SO_4^{2-} ions removed using modification of the method described by (Pujiastuti et al., 2015).

3.3.5 Percentage of Mg^{2+} , K^+ and SO_4^{2-} ions in the Precipitated Salts by EDAX

Analysis

The EDAX analysis showed that the precipitated salts consisted of 13.9% Mg^{2+} ions, 2.1% K^+ ions and 28.4% SO_4^{2-} ions similar to the results obtained by (Pujiastuti et al., 2015).

Table 3.1 Results showing Percentage Ionic Composition of Mg^{2+} , K^+ and SO_4^{2-} .

Mg^{2+}	K^+	SO_4^{2-}
13.9%	2.1%	28.4%

3.3.6 Production of High Grade Sodium Chloride Salt

Sea water was concentrated through evaporation in a stainless steel tank of volume of about 1000 cm³. The concentrated sea water was then heated to a temperature of 150°C to obtain impure sodium chloride crystals (unrefined sodium chloride). The unrefined sodium chloride was ground to a desired solid particle size by a grinding mill. The ground unrefined sodium chloride salt was loaded into the feed hopper. The feed hopper was agitated by a vibrator which caused separation of the fine solid unrefined salt crystals from the bigger salt crystals through the grate into the stainless steel container. The fine solid unrefined salt crystals were transported by a conveyor belt into a washer compartment for a refined sodium chloride salt to be produced. In the washer, fine and loose particles of impurities such as gypsum and fine sand were separated from the impure salt by counter current effects with upward flowing brine. The quality of the refined sodium chloride salt produced depends on

the efficiency of the brine flow. From the washer, the refined sodium chloride salt was pumped into a solid-liquid classifier for a pure solid-liquid sodium chloride to be produced. The mass of the pure solid-liquid sodium chloride produced was measured before drying. The solid-liquid sodium chloride was placed in a stainless steel container and heated by an electric heater to a temperature of about 150 °C for pure sodium chloride crystals to be obtained. The mass of the pure sodium chloride crystals was measured using a mass balance; and the produced sodium chloride salt was analysed for moisture content.

3.3.7 Determination of the Moisture Content of the High Grade Sodium Chloride Salt

Mass of high grade NaCl produced before drying (M_0) = 250kg.

Mass of high grade NaCl produced after drying (M_1) = 249.25kg.

Hence % moisture content of the high grade NaCl salt = $\frac{250 - 249.25}{250} = 0.3\%$

3.3.8 Recrystallization of the High Grade Sodium Chloride Salt

400g of the produced sodium chloride salt was placed in a beaker mounted on a heating mantle. 150 ml of distilled water was added to the salt just to melt it whilst being stirred and allowed to boil (100 °C) for 15 minutes. The beaker containing the boiled salt solution was covered and then placed undisturbed in a water bath containing ice cubes for 30 minutes. The settled upgraded solid sodium chloride salt was separated from the sodium chloride salt solution through filtration. The mass of the solid sodium chloride salt measured was 399.3g. The recrystallized salt produced (396.2g) was recrystallized again by the method described above and the mass of recrystallized salt (second recrystallization) was 395.1g. The process was repeated three times and the total mass of recrystallized NaCl salt obtained was 1186.1g.

Total mass of salt used in the recrystallization process was 1200g. The total mass of sodium chloride produced after recrystallization was 1186.1g.

3.3.9 Determination of Percentage Purity of the High Grade Sodium Chloride Salt

The percentage purity was calculated as mass of dried NaCl to the mass of the NaCl used in

the recrystallization process. Percentage Purity of the high grade NaCl = $\frac{1186.1g}{1200g} \times 100 =$

98.84%.

3.4 Preparation of the Saltbrine

Thirty degrees salometer (30° SAL) brine strength was prepared by dissolving 85.7g of sodium chloride salt of purity 99.9% in a pure distilled water; and stirred to dissolve the salt completely and the total volume made to 1000ml by modifying the method described by (Hilderbrand et al., 2013). A salometer was used to check the value of the brine strength prepared. The procedure was repeated for 40°, 50°, 60° and 70° SAL by dissolving sodium chloride salt of masses 117.7, 151.6, 187.8 and 226.1g respectively in distilled water.

Table 3.4. 1: Sodium Chloride Brine Table.

Salometer Degrees (°SAL)	% NaCl by weight	g/L NaCl	Specific Gravity
30	7.919	85.7	1.058
40	10.558	117.7	1.078
50	13.198	151.6	1.098
60	15.837	187.8	1.118
70	18.477	266.1	1.139

3.5 Experimental Protocol of Electrolysis

A pure distilled water of volume 500ml whose temperature 301.3K and pH=7.0 had been measured using a Bench-top pH meter was placed in the cylindrical plastic container of the cathode compartment of the electrolytic cell described earlier. An equal volume of 30° SAL brine strength whose specific gravity 1.078 had been measured using a hydrometer was placed in the cylindrical plastic container of the anode compartment. The length of the salt bridge (electrode gap) connecting the two plastic containers was 6.0cm. Each compartment of the electrolytic cell carried one graphite electrode (total surface area of each electrode was 95.77cm²). The electrodes were connected to the rectifier as described earlier. The voltage of the rectifier was set to 80V; corresponding current 0.15A registered was recorded at time 0 min. Temperature, pH of the distilled water and the specific gravity of the saltbrine as well as current were recorded every 30 mins till a constant pH value was obtained. The process was repeated for 40°, 50°, 60° and 70° SAL brine strengths at 80V and 6.0 cm electrode gap; 30°, 40°, 50°, 60° and 70° SAL at 70V and 6.0cm electrode gap; 30°, 40°, 50°, 60° and 70° SAL at 60V and 6.0cm electrode gap; 30°, 40°, 50°, 60° and 70° SAL at 50V and 6.0cm electrode gap; 30°, 40°, 50°, 60° and 70° SAL at 40V and 6.0cm electrode gap. The highest pH = 13.84 of the catholyte at 348K was obtained in 4hours and this corresponded to 50° SAL, specific gravity 1.028 of the anolyte at 80V and the registered current was 3.01A.

The optimization process continued maintaining 50° SAL, 80V and 6.0 cm electrode gap. The electrode number of each compartment was increased by one rod (electrode) after each experiment till each compartment had five electrodes. The highest pH = 13.88 of the catholyte at 360.2K was obtained at 5 electrodes in 2 hours and this corresponded to specific gravity 1.086 of the anolyte and the current registered was 5.39A. The process continued maintaining 50° SAL, 80V, 5 electrodes in each compartment and the electrode gap was

increased from 6.0 cm to 10.0 cm by an increment of 1.0 cm after each experiment. The highest pH = 13.88 of the catholyte at 360.3K was obtained at 6.0cm electrode gap in 2 hours and this corresponded to specific gravity 1.089 of the anolyte and the current registered was 5.40A.

3.6 Test for the Presence of Sodium Hydroxide

5 ml of 1.5M ammonium nitrate solution were mixed with 5 ml of 0.5M silver nitrate solution. 10 ml of 5% dextrose solution were poured into a Florence flask that had been rinsed with acetone and had been allowed to air dry completely. To the dextrose solution in the Florence flask, 10ml of the combined mixture of ammonium nitrate solution and silver nitrate solution prepared above were added. 10 ml of 10% catholyte solution were added to the solution in the Florence flask and the flask stoppered. The stoppered flask was gently swirled to mix the contents and the final solution formed was made to come into contact with the inner surface of the flask including the neck by rotating the flask continuously whilst tilted. Bright and shiny silver ‘mirror’ formed within two minutes in the inner surface of the flask indicating the presence of sodium hydroxide in the catholyte solution following the method described by (Batavia, 2004).

3.7 Quantitative Determination of Sodium Hydroxide.

20 ml of the catholyte solution of pH 13.88 were titrated against 0.952M HCl solution using methyl orange as indicator. The average volume of HCl solution used was 9.67 ml. Mass of sodium hydroxide produced was 0.368g.

3.8 Percentage Yield of Sodium Hydroxide

Actual Yield of NaOH

Total volume of the catholyte solution was 500ml. Average volume of 9.67ml of $\text{HCl}_{(\text{aq})}$ solution of 0.952M were titrated against 20ml of the catholyte solution using methyl orange as an indicator. Mass of $\text{NaOH}_{(\text{aq})}$ obtained in the 20ml of the catholyte solution was 0.368g. Therefore total mass (actual yield) of $\text{NaOH}_{(\text{aq})}$ in the 500ml of the catholyte solution was 9.200g.

Theoretical Yield of NaOH

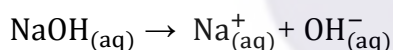
According to Faraday's first law of electrolysis, $m = ZIt$, where Z = electrochemical equivalent of sodium ($2.38 \times 10^{-4} \text{ g/C}$).

I = Current (5.40A).

t = time in secs (7200s).

m = mass of Na produced at the cathode compartment = $2.38 \times 10^{-4} \times 5.40 \times 7200 = 9.253\text{g}$.

Dissociation of NaOH



Moles of $\text{Na}_{(\text{aq})}^{+} = \frac{9.253}{23} = 0.402$ moles.

Hence, moles of $\text{NaOH}_{(\text{aq})}$ in the catholyte solution = 0.402 moles.

Therefore mass of $\text{NaOH}_{(\text{aq})}$ (theoretical yield) in the catholyte solution = $0.402 \times 40 = 16.08\text{g}$.

Percentage yield of $\text{NaOH}_{(\text{aq})} = \frac{\text{Actual yield}}{\text{Theoretical yield}} \times 100$.

Percentage yield of $\text{NaOH}_{(\text{aq})} = \frac{9.2}{16.08} \times 100 = 57.22\%$.

The next chapter shows results obtained from the experimental work and sets out to explain the conditions under which the desired product is maximum.



CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Effect of Brine Strength and Applied Voltage on the pH of NaOH.

As set out in the objective of the study, the quality of NaCl produced was determined by measuring the pH of the NaOH obtained. Table 4.1.1 to 4.1.5 show results obtained for varying brine strengths at 80V, 6.0 cm electrode gap and 1 electrode in both anode and cathode compartment.

Table 4. 1.1: Results of pH, Time, Temperature, Specific Gravity and Current at 30⁰ SAL and at 80V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.05	0.15	7.919	0	301.3	1.078	0.188
7.10	0.24		1800	301.7	1.022	0.300
7.66	0.28		3600	301.8	1.018	0.350
8.16	0.35		5400	301.9	1.013	0.440
9.67	0.42		7200	303.4	1.011	0.523
10.23	0.56		9000	307.1	1.009	0.700
10.43	0.62		10800	308.0	1.005	0.775
12.55	0.68		12600	308.6	1.002	0.850
12.72	0.74		14400	314.6	1.001	0.925

From Table 4.1.1, the pH of NaOH increases with increase in electric current and reaction time. This trend could be explained by the fact that high currents as a result of the high applied voltage (80V) favoured the feasibility of the reaction by facilitating the dissociation of more NaCl into Na⁺ and Cl⁻ ions as well as H₂O into H⁺ and OH⁻ ions in both the anode and cathode compartments respectively. The high currents also increased the mobility of the ions in solution by causing the Na⁺ ions to migrate faster to combine with the hydroxyl ions (OH⁻) in the cathode compartment to form more NaOH as indicated by the magnitude of the

pH of the catholyte. The rise in temperature of the catholyte with increase in reaction time as observed in Table 4.1.1 is also due to increase in electric current and the observed rise in temperature did not offset the amount of NaOH produced during the course of the reaction. The specific gravity of the saltbrine decreases as the reaction proceeded showing that more of the NaCl were converted to NaOH as the reaction time increased. In Table 4.1.1, the experiment could not be carried out beyond a pH of 12.72 because the design of the experiment was within a specific time of 14400 seconds. For subsequent results from Table 4.2.1 to 4.3.3, although 14400 seconds has not been attained, the experiment was limited to a certain pH at the end of the reaction so as to preserve the integrity of the anode and cathode compartments by preventing melting and also avoiding decomposition of the desired product.

Table 4.1.2 depicts results obtained using 40⁰ SAL brine strength under the conditions of 80V, 1 electrode in both anode and cathode compartment and 6.0 cm electrode gap.

Table 4.1. 2: Results of pH, Time, Temperature, Specific Gravity and Current at 40⁰ SAL and at 80V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.11	0.15	10.558	0	302.7	1.078	0.188
9.64	0.31		1800	307.4	1.061	0.388
10.43	0.35		3600	309.1	1.042	0.440
12.07	0.40		5400	314.7	1.035	0.500
12.17	0.62		7200	319.9	1.021	0.775
12.54	1.08		9000	326.7	1.013	1.350
13.34	2.50		10800	337.8	1.009	3.125
13.82	2.64		12600	347.6	1.004	3.300
13.83	2.88		14400	349.3	1.001	3.600

The trend in the pH of the NaOH observed in Table 4.1.2 is similar to that observed in Table 4.1.1. However the rise in pH of the NaOH in Table 4.1.2 is more appreciable than that observed in Table 4.1.1. A maximum pH 13.83 of NaOH obtained in Table 4.1.2 as compared to pH 12.72 obtained in Table 4.1.1 under the same conditions of experiment shows that the brine strength 40⁰ SAL favoured the formation of NaOH better than 30⁰ SAL.

Table 4.1.3 shows the trend in pH of the NaOH measured after each reaction time.

Table 4.1. 3: Results of pH, Time, Temperature, Specific Gravity and Current at 50⁰ SAL and at 80V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.09	0.15	10.558	0	301.9	1.098	0.188
9.87	0.36		1800	309.2	1.072	0.450
10.56	0.42		3600	311.1	1.069	0.525
12.12	0.46		5400	314.9	1.066	0.575
12.48	0.66		7200	321.2	1.054	0.825
12.84	1.12		9000	328.4	1.048	1.400
13.44	2.63		10800	340.8	1.036	3.288
13.60	2.96		12600	348.9	1.028	3.700
13.84	3.01		14400	350.2	1.026	3.763

The trend in pH observed in Table 4.1.3 is the same as that observed in Tables 4.1.1 and 4.1.2. However a maximum pH 13.84 observed in Table 4.1.3 shows that the brine strength 50⁰ SAL favoured the formation of the desired product (NaOH) better than 30⁰ and 40⁰ SAL brine strengths under the same conditions of experiment.

Table 4.1. 4: Results of pH, Time, Temperature, Specific Gravity and Current at 60⁰ SAL and at 80V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.09	0.15	15.12	0	301.6	1.118	0.188
10.52	0.80		1800	326.3	1.109	1.000
11.01	1.60		3600	334.4	1.106	2.000
11.24	3.20		5400	341.3	1.102	4.000
11.52	3.50		7200	356.4	1.090	4.375
11.80	4.40		9000	358.3	1.060	5.500
12.12	5.02		10800	358.9	1.021	6.275
12.26	5.12		12600	359.2	1.011	6.400
12.46	5.16		14400	360.1	1.009	6.450

The pH of the NaOH at the end of the reaction time with 60⁰ SAL from Table 4.1.4 is 12.46 and 11.62 with 70⁰ SAL in Table 4.1.5. The observation is inconsistent with that observed in Tables 4.1.1 to 4.1.3. The result is due to the fact that the applied voltage was not sufficient to cause complete dissociation of the NaCl and H₂O molecules into their primitive states to facilitate the formation of the desired product.

Table 4.1. 5: Results of pH, Time, Temperature, Specific Gravity and Current at 70⁰ SAL at 80V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.04	0.15	10.558	0	301.9	1.098	0.188
10.68	0.36		1800	309.2	1.072	0.450
11.00	0.42		3600	311.1	1.069	0.525
11.12	0.46		5400	314.9	1.066	0.575
11.23	0.66		7200	321.2	1.054	0.825
11.36	1.12		9000	328.4	1.048	1.400
11.42	2.63		10800	340.8	1.036	3.288
11.53	2.96		12600	348.9	1.028	3.700
11.62	3.01		14400	350.2	1.026	3.763

Table 4.1.6 to 4.1.25 show results obtained for pH of NaOH with the same controlled parameters mentioned in the previous tables but at 70V.

As delineated in the research objectives, the influence of voltage on the pH of NaOH was investigated. Table 4.1.6 to 4.1.25 depict results of pH dependence on the applied voltage.

Table 4.1. 6: Results of pH, Time, Temperature, Specific Gravity and Current at 30⁰ SAL at 70V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.08	0.15	7.919	0	301.2	1.038	0.188
7.12	0.22		1800	301.5	1.018	0.275
7.54	0.26		3600	301.8	1.016	0.325
8.12	0.34		5400	301.9	1.014	0.425
9.61	0.40		7200	302.9	1.011	0.500
10.18	0.53		9000	306.8	1.008	0.663
10.38	0.60		10800	307.5	1.006	0.750
12.54	0.65		12600	308.6	1.002	0.813
12.58	0.71		14400	310.2	1.001	0.888

From Tables 4.1.6 to 4.1.10, the applied voltage was 70V and the remaining three parameters were kept constant. The pH values for NaOH for all the brine strengths are much lower at 70V compared with equal brine strengths electrolyzed at 80V. The highest pH of NaOH is 13.84 at 80V with 50⁰ SAL brine strength from Table 4.1.3. Meanwhile from Table 4.1.8 with 50⁰ SAL brine strength electrolyzed at 70V, the maximum pH for NaOH obtained from the present study is 13.72 at the same reaction time of 14400 seconds as observed from Table 4.1.3. The subsequent tables; Table 4.1.1 to 4.1.25 show similar trend when the same brine strengths were electrolyzed at 60, 50 and 40V. Although when the brine strengths were electrolyzed at 80V, 50⁰ SAL was observed to be the optimum with pH of NaOH 13.84 at the end of the reaction time. The optimum brine strength 50⁰ SAL when electrolyzed at 40V at 14400 seconds, the maximum pH of NaOH obtained was 13.22 indicating that the applied voltage had a significant influence on the amount of NaOH produced as observed in the pH values. The trend could be explained by the fact that the voltages were associated with high electric currents which facilitated the dissociation of NaCl and H₂O molecules into their respective ions. These high currents as a result of the high voltage also increased the mobility of Na⁺ ions from the anode to the cathode compartment for combination with the hydroxyl ions for formation of the desired product (NaOH).

Table 4.1. 7: Results of pH, Time, Temperature, Specific gravity and Current at 40⁰ SAL at 70V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.05	0.15	10.558	0	302.2	1.058	0.188
9.58	0.28		1800	306.8	1.049	0.350
10.40	0.32		3600	308.5	1.040	0.400
12.10	0.36		5400	313.7	1.032	0.450
12.14	0.58		7200	320.9	1.018	0.725
12.50	1.06		9000	324.8	1.011	1.325
13.30	2.44		10800	336.9	1.009	3.05
13.56	2.58		12600	344.6	1.002	3.225
13.60	2.62		14400	345.2	1.001	3.275

Table 4.1. 8: Results of pH with Time, Temperature, Specific Gravity and Current at fixed Brine strength 50⁰ SAL at 70V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.12	0.15	13.198	0	301.9	1.098	0.188
9.84	0.32		1800	309.2	1.072	0.400
10.52	0.38		3600	311.1	1.069	0.475
12.10	0.40		5400	314.9	1.066	0.500
12.44	0.62		7200	321.2	1.054	0.775
12.81	1.10		9000	328.4	1.048	1.375
13.43	2.58		10800	340.8	1.036	3.225
13.67	2.89		12600	348.9	1.028	3.613
13.72	2.93		14400	349.3	1.023	3.663

Table 4.1. 9: Results of pH, Time, Temperature, Specific Gravity and Current at 60⁰ SAL at 70V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.06	0.15	15.12	0	301.9	1.118	0.188
10.48	0.76		1800	324.6	1.112	0.95
10.96	1.58		3600	332.1	1.108	1.975
11.16	3.18		5400	340.8	1.104	3.975
11.34	3.46		7200	354.7	1.096	4.325
11.75	4.38		9000	355.4	1.084	5.475
12.18	5.00		10800	357.8	1.078	6.250
12.22	5.08		12600	358.9	1.066	6.350
12.26	5.12		14400	359.6	1.058	6.400

Table 4.1. 10: Results of pH, Time, Temperature, Specific Gravity and Current at 70⁰ SAL at 70V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.11	0.15	18.477	0	301.4	1.139	0.188
10.58	0.92		1800	326.8	1.132	1.15
11.10	1.78		3600	335.3	1.128	2.225
11.24	3.40		5400	340.2	1.124	4.250
11.32	3.70		7200	348.6	1.119	4.625
11.42	4.60		9000	356.2	1.108	5.750
11.48	5.02		10800	363.6	1.009	6.275
11.54	5.15		12600	365.2	1.004	6.438
11.63	5.24		14400	365.4	1.001	6.450

Table 4.1. 11: Results of pH, Time, Temperature, Specific Gravity and Current at 30 °SAL at 60V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.11	0.15	7.919	0	301.7	1.058	0.188
7.18	0.24		1800	301.8	1.016	0.300
7.48	0.28		3600	301.9	1.012	0.350
8.16	0.36		5400	302.0	1.011	0.450
9.59	0.42		7200	302.4	1.009	0.525
9.66	0.50		9000	305.3	1.004	0.625
10.28	0.58		10800	306.5	0.98	0.725
10.68	0.64		12600	307.2	0.94	0.800
11.74	0.78		14400	310.4	0.92	0.975

Table 4.1. 12: Results of pH, Time, Temperature, Specific Gravity, Current and at 40 °SAL at 60V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.12	0.15	10.558	0	302.1	1.078	0.188
9.69	0.22		1800	305.9	1.075	0.275
10.36	0.30		3600	307.4	1.056	0.375
12.12	0.34		5400	310.9	1.044	0.425
12.16	0.54		7200	318.9	1.038	0.675
12.48	1.04		9000	320.8	1.032	1.300
13.03	2.42		10800	332.4	1.024	3.025
13.20	2.56		12600	340.9	1.016	3.200
13.34	2.80		14400	341.6	1.014	3.500

Table 4.1. 13: Results of pH, Time, Temperature, Specific Gravity and Current at 50 °SAL and at 60V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.13	0.15	13.198	0	301.9	1.098	0.188
9.80	0.30		1800	308.2	1.086	0.375
10.50	0.36		3600	310.6	1.072	0.450
12.12	0.40		5400	313.5	1.068	0.500
12.42	0.58		7200	320.2	1.050	0.725
12.78	1.08		9000	324.3	1.044	1.350
13.40	2.44		10800	338.7	1.032	3.050
13.58	2.79		12600	346.8	1.023	3.488
13.62	2.83		14400	347.3	1.018	3.538

Table 4.1. 14: Results of pH, Time, Temperature, Specific Gravity and Current at 60 °SAL and at 60 V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.14	0.15	15.837	0	301.4	1.118	0.188
10.46	0.72		1800	322.4	1.114	0.900
10.92	1.52		3600	330.8	1.112	1.900
11.14	3.14		5400	338.1	1.109	3.925
11.30	3.38		7200	350.6	1.098	4.225
11.68	4.30		9000	353.8	1.089	5.375
12.12	4.78		10800	354.5	1.082	5.975
12.20	5.00		12600	356.6	1.078	6.250
12.35	5.10		14400	357.4	1.072	6.375

Table 4.1. 15: Results of pH, Time, Temperature, Specific Gravity and Current at 70 °SAL and at 60V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.18	0.15	18.477	0	301.4	1.139	0.188
10.54	0.90		1800	324.4	1.136	1.125
11.10	1.74		3600	332.6	1.130	2.175
11.20	3.38		5400	338.6	1.126	4.225
11.28	3.68		7200	344.9	1.124	4.600
11.38	4.56		9000	352.9	1.118	5.700
11.44	5.02		10800	364.8	1.109	6.275
11.52	5.08		12600	365.0	1.106	6.350
11.56	5.11		14400	365.4	1.104	6.388

Table 4.1. 16: Results of pH, Time, Temperature, Specific Gravity and Current at 30° SAL and at 50V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.08	0.15	7.919	0	301.3	1.058	0.188
7.20	0.30		1800	301.6	1.018	0.375
7.50	0.32		3600	301.7	1.014	0.400
8.24	0.40		5400	301.8	1.013	0.500
9.60	0.45		7200	302.1	1.011	0.563
9.74	0.60		9000	304.6	1.010	0.750
10.31	0.65		10800	305.2	1.006	0.813
10.72	0.71		12600	306.4	0.99	0.888
11.84	0.92		14400	309.7	0.96	1.15

Table 4.1. 17: Results of pH, Time, Temperature, Specific Gravity and Current at 40⁰ SAL and at 50V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.11	0.15	10.558	0	301.1	1.078	0.188
7.22	0.31		1800	301.8	1.077	0.388
7.53	0.33		3600	301.9	1.070	0.413
8.30	0.42		5400	302.1	1.066	0.525
9.64	0.47		7200	302.4	1.060	0.588
9.78	0.64		9000	304.8	1.052	0.800
10.40	0.68		10800	305.6	1.048	0.850
10.82	0.79		12600	306.9	1.042	0.988
12.01	0.98		14400	310.2	1.036	1.225

Table 4.1.18: Results of pH, Time, Temperature, Specific Gravity and Current at 50⁰ SAL and at 50V.

pH	Current (A)	% Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.09	0.15	13.198	0	301.3	1.098	0.188
7.25	0.34		1800	301.9	1.093	0.425
7.58	0.36		3600	302.2	1.090	0.450
8.36	0.44		5400	302.6	1.088	0.550
9.68	0.52		7200	302.9	1.084	0.650
10.82	0.68		9000	304.9	1.080	0.850
11.45	0.73		10800	305.8	1.076	0.913
12.88	0.84		12600	307.1	1.072	1.050
13.44	1.01		14400	310.6	1.069	1.263

Table 4.1. 189: Results of pH, Time, Temperature, Specific Gravity and Current at 60° SAL and at 50V.

pH	Current (A)	%Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.12	0.15	15.837	0	301.1	1.118	0.188
7.30	0.36		1800	302.0	1.116	0.450
7.60	0.39		3600	302.6	1.111	0.488
8.38	0.48		5400	302.9	1.110	0.600
9.71	0.57		7200	303.2	1.109	0.713
9.86	0.74		9000	305.1	1.106	0.925
10.49	0.77		10800	305.6	1.101	0.963
10.93	0.85		12600	307.4	1.080	1.063
12.11	1.06		14400	311.2	1.065	1.325

Table 4.1. 20: Results of pH, Time, Temperature, Specific Gravity and Current at 70° SAL and at 50V.

pH	Current (A)	%Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.09	0.15	18.477	0	301.6	1.139	0.188
7.34	0.40		1800	302.3	1.138	0.500
7.65	0.44		3600	302.8	1.135	0.550
8.44	0.54		5400	303.1	1.132	0.675
9.76	0.63		7200	303.6	1.130	0.788
9.92	0.80		9000	305.4	1.128	1.000
10.56	0.84		10800	306.0	1.124	1.050
11.10	0.90		12600	308.1	1.120	1.125
12.20	1.10		14400	312.2	1.116	1.375

Table 4.1. 191: Results of pH, Time, Temperature, Specific Gravity and Current at 30⁰ SAL and at 40V.

pH	Current (A)	%Weight of NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.09	0.15	7.919	0	301.1	1.058	0.188
7.18	0.28		1800	301.4	1.054	0.35
7.47	0.30		3600	301.2	1.050	0.375
8.19	0.36		5400	301.6	1.044	0.450
9.46	0.41		7200	301.5	1.039	0.513
9.69	0.56		9000	302.0	1.034	0.700
10.28	0.60		10800	304.1	1.029	0.750
10.68	0.66		12600	305.9	1.024	0.825
11.70	0.88		14400	309.2	1.021	1.100

Table 4.1. 20: Results of pH, Time, Temperature, Specific Gravity and Current at 40⁰ SAL and at 40V.

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm²)
7.09	0.15	10.558	0	301.0	1.078	0.188
7.20	0.29		1800	301.4	1.077	0.363
7.50	0.30		3600	301.5	1.074	0.375
8.27	0.40		5400	302.0	1.070	0.500
9.61	0.44		7200	302.2	1.066	0.550
9.72	0.60		9000	304.4	1.062	0.750
10.36	0.64		10800	305.2	1.058	0.800
10.78	0.75		12600	306.4	1.054	0.938
12.00	0.95		14400	310.0	1.050	1.188

Table 4.1. 21: Results of pH, Time, Temperature, Specific Gravity and Current at 50⁰ SAL and at 40V.

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.06	0.15	13.198	0	301.1	1.098	0.188
7.21	0.32		1800	301.6	1.095	0.400
7.55	0.33		3600	302.0	1.092	0.413
8.34	0.41		5400	302.4	1.090	0.513
9.65	0.50		7200	302.6	1.088	0.625
10.79	0.64		9000	304.5	1.084	0.800
11.42	0.70		10800	305.3	1.082	0.875
12.83	0.81		12600	306.8	1.079	1.013
13.22	0.99		14400	310.2	1.075	1.238

Table 4.1. 224: Results of pH, Time, Temperature, Specific Gravity and Current at 60⁰ SAL and at 40V.

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.11	0.15	15.837	0	301.3	1.118	0.188
7.29	0.32		1800	301.9	1.117	0.400
7.58	0.36		3600	302.2	1.115	0.450
8.36	0.43		5400	302.4	1.112	0.538
9.68	0.54		7200	303.0	1.109	0.675
10.84	0.72		9000	304.8	1.104	0.900
11.45	0.74		10800	305.1	1.100	0.925
12.90	0.83		12600	306.9	1.090	1.038
13.08	1.03		14400	311.0	1.080	1.288

Table 4.1. 235: Results of pH, Time, Temperature, Specific Gravity and Current at 70⁰ SAL and at 40V.

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.05	0.15	18.477	0	301.4	1.139	0.188
7.32	0.38		1800	302.0	1.138	0.475
7.61	0.40		3600	302.5	1.136	0.500
8.40	0.52		5400	303.0	1.134	0.650
9.72	0.60		7200	303.2	1.131	0.750
9.88	4.0.76		9000	305.1	1.129	0.950
10.53	0.80		10800	305.8	1.126	1.000
11.00	0.88		12600	306.9	1.124	1.100
12.18	1.10		14400	311.8	1.120	1.375

4.2 Effect of Electrode Number on the pH of NaOH.

Table 4.2.1 to 4.2.4 show results with optimum brine strength and applied voltage and the dependence of the pH of NaOH with varying number of electrodes in both the anode and cathode compartments.

Table 4.2.1: Results showing variation of pH with Time at (50⁰ SAL, 80V, 6.0 cm Electrode Gap, 2 electrodes in Anode and Cathode Compartments).

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.11	0.15	15.837	0	300.1	1.118	0.094
9.90	0.60		1800	318.2	1.112	0.375
9.96	1.32		3600	326.9	1.100	0.825
10.50	2.80		5400	334.8	1.091	1.750
12.30	3.10		7200	340.4	1.088	1.938
12.60	4.42		9000	348.5	1.076	2.763
12.84	4.64		10800	350.8	1.069	2.900
13.85	4.88		12600	354.6	1.048	3.050

In Table 4.2.1, two electrodes were used in both anode and cathode compartments; the maximum pH of NaOH obtained was 13.85 at a reaction time of 12600 seconds. However, the pH of NaOH was observed to increase appreciably at a reduced reaction time when the number of electrodes were increased from two to five as shown in Table 4.2.1 to 4.2.4. In Table 4.2.2, three electrodes were used. The maximum pH of NaOH obtained was 13.86 at a reaction time of 10800 seconds. A similar trend was observed in Table 4.2.3 with four electrodes. The pH of NaOH was 13.87 at a reaction time of 9000 seconds. The highest pH 13.88 of NaOH was obtained at a reaction time of 7200 seconds when five electrodes were used as shown in Table 4.2.4. The trend in the results indicates that the pH of the NaOH depends on the number of electrodes. This observation is due to the fact that the higher the number of electrodes, the greater the surface area of the electrodes in contact with their respective electrolytes. The larger surface area of the electrodes increased the quantity of effective charge per unit area which facilitated the dissociation of more NaCl in the anolyte compartment leading to the formation of more NaOH in the catholyte compartment as indicated by the magnitude of the pH values.

Table 4.2.2: Results Showing Variation of pH with Time at (50⁰ SAL, 80V, 6.0 cm Electrode Gap, 3 Electrodes in Anode and Cathode Compartments).

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.08	0.15	15.837	0	302.3	1.118	0.063
10.52	0.82		1800	319.4	1.110	0.342
12.42	1.52		3600	328.2	1.096	0.633
12.62	3.11		5400	336.8	1.083	1.296
12.88	3.24		7200	348.7	1.072	1.350
13.80	4.63		9000	352.9	1.066	1.929
13.86	5.00		10800	358.9	1.053	2.083

Table 4.2.3: Results Showing Variation of pH with Time at (50⁰ SAL, 80V, 6.0 cm Electrode Gap, 4 Electrodes in Anode and Cathode Compartments).

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.06	0.15	15.837	0	302.1	1.118	0.047
11.26	1.76		1800	329.6	1.110	0.550
12.74	3.20		3600	338.2	1.090	1.000
12.90	3.63		5400	349.4	1.088	1.134
13.82	4.89		7200	356.2	1.076	1.528
13.87	5.29		9000	359.5	1.066	1.653

Table 4.2.4: Results Showing Variation of pH with Time at (50⁰ SAL, 80V, 6.0 cm Electrode Gap, 5 Electrodes in Anode and Cathode Compartments).

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.06	0.15	15.837	0	302.9	1.118	0.038
11.74	3.12		1800	336.5	1.100	0.780
12.74	4.16		3600	350.2	1.098	1.040
13.86	4.88		5400	356.9	1.091	1.220
13.88	5.40		7200	360.3	1.089	1.350

The subsequent results set out to investigate the effect of gaps between the electrodes on the pH of NaOH.

4.3 Effect of Gaps between the Electrodes on the pH of NaOH.

As delineated in the objective of the research, Table 4.3.1 to 4.3.3 illustrate results of the effect of the gaps between the electrodes on the pH of NaOH. Three controlled parameters are constant and the gaps between the electrodes are varied to ascertain their influence on the pH of NaOH.

Table 4.3.1: Results Showing Variation of pH with Time at (50⁰ SAL, 80V, 7.0 cm Electrode Gap, 5 Electrodes in Anode and Cathode Compartments).

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.12	0.15	15.837	0	302.9	1.118	0.038
11.18	3.10		1800	335.5	1.114	0.775
12.70	4.12		3600	348.4	1.101	1.030
12.88	4.84		5400	354.3	1.098	1.210
13.85	5.31		7200	358.2	1.092	1.328
13.87	5.34		9000	359.7	1.093	1.335

From the tables, the pH of NaOH is observed to decrease with increase in the gaps between the electrodes at the end of the reaction. In Table 4.3.1, the electrode gap was 7.0 cm. The pH of NaOH at the end of the reaction is 13.87 at a reaction time of 9000 seconds. The pH reduced to 13.86 at a reaction time of 10800 seconds in Table 4.3.1 when the electrode gap was increased to 8.0 cm. In Table 4.3.2, pH of NaOH is 13.85 at a reaction time of 12600 seconds when the electrode gap was 9.0 cm. A similar effect is observed in Table 4.3.3 when the electrode gap was increased to 10.0 cm. The pH of NaOH is 13.84 at a reaction time of 14400 seconds. The highest pH 13.88 of NaOH was observed in Table 4.3.1 at a reaction time of 7200 seconds when the electrode gap was 6.0 cm under the same conditions of experiment. The trend shows that the gap between the electrodes has significant influence

on the pH of the NaOH. The observation could be explained by the fact that ions travel during reactions in order to cause product formation. By increasing inter electrode distance, the Na^+ ions in the anode compartment had to travel relatively longer distances to combine with the hydroxyl ions (OH^-) in the cathode compartment to form NaOH. A shorter inter electrode distance would therefore imply that these ions would combine more readily and comparatively at reduced reaction time. However, an electrode gap below 6.0 cm was not used in this work due to the dimensions of the anode and cathode compartments. An electrode gap below 6.0 cm could have led to short-circuiting and electric sparks.

Table 4.3.2: Results Showing Variation of pH with Time at (50⁰ SAL, 80V, 8.0 cm Electrode Gap, 5 Electrodes in Anode and Cathode Compartments).

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.12	0.15	15.837	0	302.9	1.118	0.038
11.18	3.10		1800	335.5	1.114	0.775
12.70	4.12		3600	348.4	1.101	1.030
12.88	4.84		5400	354.3	1.098	1.210
13.80	5.25		7200	358.2	1.092	1.313
13.84	5.30		9000	359.7	1.093	1.325
13.86	5.33		10800	359.9	1.090	1.333

Table 4.3.3: Results Showing Variation of pH with Time at (50⁰ SAL, 80V, 9.0 cm Electrode Gap, 5 Electrodes in Anode and Cathode Compartments).

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.12	0.15	15.837	0	302.9	1.118	0.038
11.18	3.10		1800	335.5	1.114	0.775
12.70	4.12		3600	348.4	1.101	1.030
12.88	4.84		5400	354.3	1.098	1.210
13.74	5.25		7200	358.2	1.092	1.313
13.78	5.28		9000	358.6	1.093	1.320
13.82	5.30		10800	359.9	1.088	1.325
13.85	5.33		12600	360.0	1.090	1.333

Table 4.3.4: Results showing variation of pH with Time at (50⁰ SAL, 80V, 10.0 cm Electrode Gap, 5 Electrodes in Anode and Cathode Compartments).

pH	Current (A)	%Weight NaCl	Time (s)	Temperature (K)	Specific gravity	Current density (A/cm ²)
7.12	0.15	15.837	0	302.9	1.118	0.038
11.18	3.08		1800	334.1	1.117	0.770
12.70	4.00		3600	346.4	1.115	1.000
12.88	4.62		5400	352.6	1.112	1.155
13.66	5.00		7200	355.4	1.110	1.250
13.73	5.14		9000	355.1	1.100	1.285
13.76	5.23		10800	356.4	1.099	1.308
13.80	5.28		12600	357.8	1.095	1.320
13.84	5.30		14400	358.5	1.088	1.325

4.4 Effects of the Optimum Parameters on the pH of NaOH.

As outlined in the research objectives, the effect of the optimum parameters were investigated to ascertain their influence on the maximization of the pH of NaOH.

4.4.1 Effect of Brine Strength

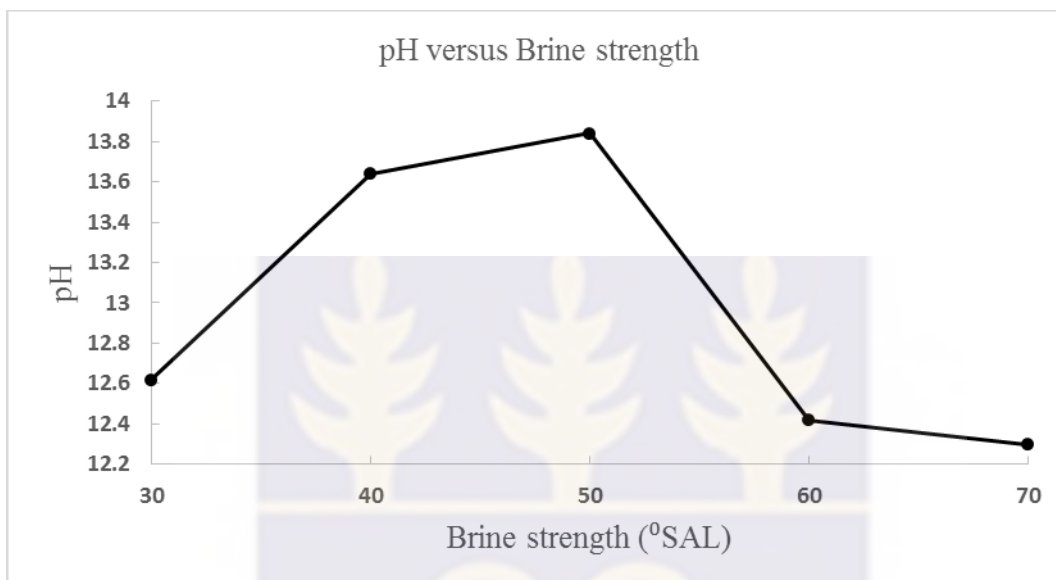


Figure 4.4.1: A graph of pH against brine strength.

To study the effect of brine strength on the production of sodium hydroxide (indicated by the magnitude of the pH of the catholyte), different brine strengths were used (Domga et al., 2016). Figure 4.4.1 shows that pH of the catholyte increase with increase in brine strength of the anolyte. Maximum pH of 13.84 of the catholyte occurred at 50° SAL. A Similar work conducted by (Saksono et al., 2013) confirmed the observed trend. The observed trend could be explained by the fact that as electric current passed through the electrolytic cell, NaCl in the anode compartment dissociated into Na^+ ions and Cl^- ions. In the same vein, H_2O in the cathode compartment dissociated into H^+ ions and OH^- ions. The positively charged Na^+ ions in the anode compartment were attracted by the negatively charged electrode (cathode). The Na^+ ions on reaching the cathode compartment formed NaOH with the OH^- in the cathode compartment. Hence increased the concentration of NaOH (pH of the catholyte).

The H^+ ions in the cathode compartment was reduced to H_2 gas at the cathode compartment. Similarly, Cl^- ions in the anode compartment were oxidized to Cl_2 gas at the anode compartment. As brine strength increased beyond 50^0 SAL, pH (amount of NaOH) decreased to a minimum value of 12.30 corresponding to a brine strength of 70^0 SAL. The decrease in pH could be explained by the fact that high brine strength could lead to the formation of blisters and hence increased in ohmic resistance leading to a decrease in NaOH production as observed by (Domga et al., 2016).

4.4.2 Effect of Gaps between the Electrodes

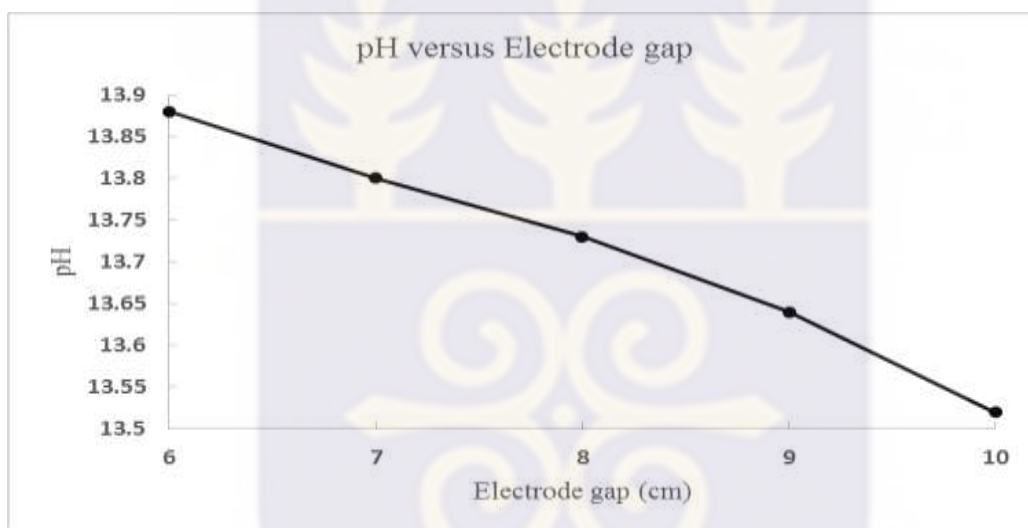


Figure 4.4. 2: A graph of pH against gaps between the electrodes.

Figure 4.4.2 shows that the pH of the catholyte decreased as the gap between the electrodes increased. Highest pH 13.88 occurred at an electrode gap of 6.0cm. A similar work carried out by (Ana, 2005) on chlor-alkali production confirmed the observed trend. Author (Leroy et al., 1979) also did a similar work and reported a comparable trend. This observed trend could be explained by the fact that the smaller the electrode gap, the lower the ohmic resistance and hence the higher the current that dissociates H_2O and $NaCl$ into H^+ , OH^- and Na^+ and Cl^- ions respectively. This high current also speeds up ions from one compartment to the other for more NaOH to be formed and hence increase in pH. However, if the gap is

very small, there is entrapment of gas bubbles between the electrodes (Nagai et al., 2003). Again, a close gap results in higher frequency of short-circuiting and electric sparks (Strathmann et al., 2004).

4.4.3 Effect of Electrode Number

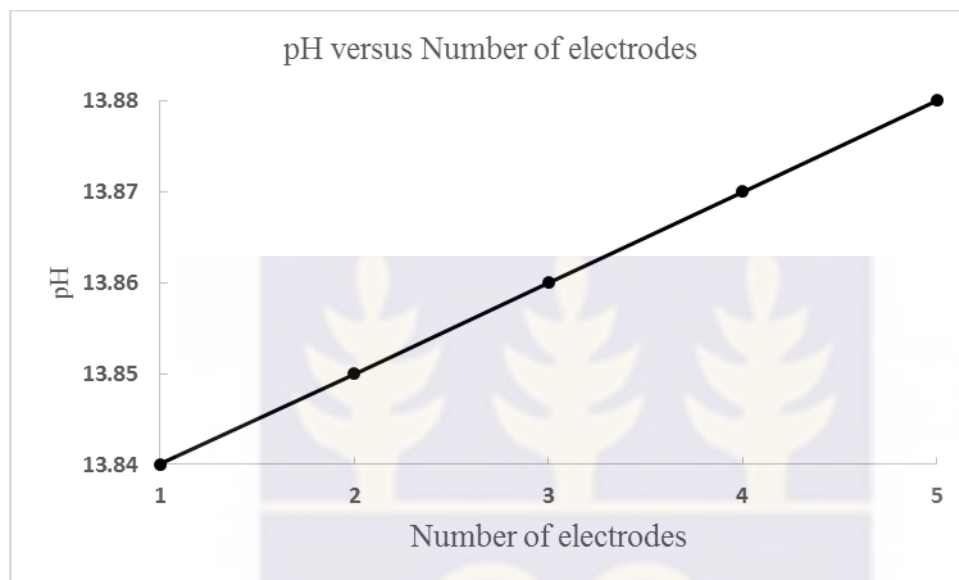


Figure 4.4.3: A graph showing the trend in pH with increasing number of electrodes.

Figure 4.4.3 indicates that the pH of the catholyte increased as the number of electrodes in each compartment increased. Similar works carried out by (Sengupta et al., 1994; Domga et al., 2016) confirmed the observed trend. The observed trend may be explained by the fact that as the number of electrodes (in the two compartments) increased, the total surface area of the electrodes in contact with their respective electrolyte also increased and hence quantity of effective charge per unit area increased which facilitated the dissociation of more NaCl in the anolyte compartment leading to the formation of more NaOH in the catholyte compartment; and hence increased the pH of the catholyte. However, when the number of electrodes in each compartment is too high, it could result in short –circuits due to reduction of inter-electrodes distance (Daneshvar et al., 2007).

4.4.4 Effect of Voltage

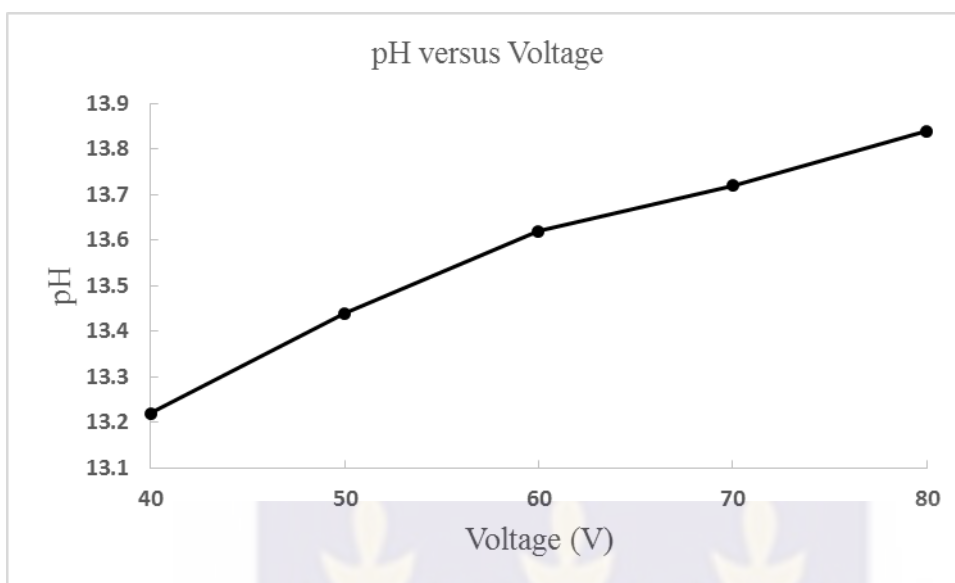


Figure 4.4.4: A graph showing the trend in pH as voltage increases.

Figure 4.4.4 shows that the pH of the catholyte increased with respect to increase in the applied voltage. Similar results were obtained by (Saksono et al., 2013; Rabbani et al., 2014). This outcome could be explained by the fact that increasing the applied voltage increase electrical charge in the electrolytic cell leading to the dissociation of more NaCl and H₂O molecules and hence formation of more NaOH and so increased pH of the catholyte. However, beyond pH 13.62 which corresponded to a voltage of 60V, the pH of the catholyte began to level due to overheating of the electrolytic cell which caused the temperature of the electrolytes to increase. The increase in temperature increased the electrical resistance and hence reduced the amount of electric charge that passed through the electrolytes. The reduction in electric charge accounted for the drop in the pH of the catholyte due to reduction in the dissociation of NaCl and H₂O molecules in both anolyte and catholyte compartments respectively.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Some factors that influence quantity of NaOH produced from NaCl through electrolysis were studied and optimized. Quantity of NaOH produced increased with increase in brine strength. Optimum brine strength obtained was 50⁰ SAL. Beyond 50⁰ SAL, the amount of NaOH produced decreased as a result of formation of blisters in the salt bridge which caused electric resistance to increase. The quantity of NaOH produced also decreased with increased in the gap between the electrodes. This is because the charged species had to travel longer distance from one compartment to the other for product formation. The optimum gap between the electrodes was 6.0cm. NaOH production was observed to increase with increased in the number of electrodes. The highest electrodes used in this experiment was 5 in each compartment. The greater the number of electrodes, the greater the number of effective charge per unit area. NaOH production increased with increased in effective voltage (which is proportional to effective current). The optimum voltage was 80V. The highest pH which corresponded to the quantity of NaOH produced was 13.88 at 360.3K and 5.40A.

5.2 Recommendation

It is recommended that further studies should focus on the optimization of temperature and current to ascertain their influence on maximization of NaOH production.

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