
A TECHNO-ECONOMIC REVIEW OF ELECTROLYTIC PRODUCTION OF HYPOCHLOROUS ACID (HOCl)

Final Project Report

OCTOBER 2020 – MARCH 2021

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2020 - 2021

ACKNOWLEDGEMENTS

First and foremost, praise be to God for giving unlimited graces to me.

I would like to express my deepest gratitude to Mr. Suha Rawhani for his valuable guidance and also for his supervision on this thesis.

I would like to acknowledge and thank my Chemical Engineering Department of BIHE University especially Mr. Erfan Rezaei.

I would like to express my sincerely thanks to all people and company managers who directly or indirectly contributed to this work.

Finally, I would like to thank my beloved family, they are always standing next to me and give me encouragement all the time, and for their pure and endless love and support. I am so lucky and proud to have them in my life.

Thank you all.

Respectfully,

Hamed Haddadzadeh

ABSTRACT

In this review electrolytic hypochlorous acid generators were investigated and their advantages and disadvantages were identified. Hypochlorous acid is a highly efficient solution for sanitizing and one hundred percent safe for human use but like all disinfection solutions, it has some disadvantages, such as low shelf life in some cases, can damage skin in high chlorine concentrations and it can cause corrosion in metals, etc. In general, bacteria, pathogens and viruses surrounded us. The hypochlorous acid could be used as disinfection solution for confronting this danger. Producing hypochlorous acid is commercial issue and companies do not allow to other people for having access to their mechanism that used for producing hypochlorous acid. So, for this case of study, emails were sent to approximately 110 companies that supply hypochlorous acid generators or producers of hypochlorous acid in the world. Only a few of them responded, about 2 companies cooperated and filled the tables that I prepared and about 3 people sent me some papers. This final report has been written according to these responded and 270 papers that I read. The result is a classification of four models of devices that produce hypochlorous acid through electrolysis from the past to the present and evaluation of the advantages and disadvantages of these four main models. Also, some criteria have been written for the feed quality of these cells, quality criteria of and the maintenance of these cell parts because these devices have ideal operating conditions and these conditions should be considered to produce better hypochlorous acid with longer shelf life.

In the following, an economic review has been written on these electrolytic cells for producing hypochlorous acid. For this case of study, the technical and economic information of the available devices has been collected. Also, to better communicate with companies that active in production of hypochlorous acid, their page addresses and contact emails have been written in appendices chapter. Based on technical and economic information, results have been obtained regarding the prices and efficiency of these hypochlorous acid generators. Also, in this work, the main problems of these devices were investigated and some recommendations have been written in the recommendation chapter to improve these problems. These recommendations are related to best device that could produce hypochlorous acid, corrosion on anode, fouling formation on the cathode, low shelf life of the hypochlorous acid, modeling the space between electrodes by simulation software and control system, etc. Also, some recommendations have been written about replacing power supply of the electrolytic cells devices by using renewable energy devices.

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Chapter One

Introduction

CHAPTER 1 - INTRODUCTION

One of the most basic human needs is the needs for a disinfectant especially today by safe disinfection solutions to protect their life from the pathogens, viruses, bacteria and all dangerous microbes. Some disinfection chemicals are very toxic and can be hazardous and It can cause irritation when contact with skin and also can rust metals, etc. These dangers do not exist with hypochlorous acid (Michael S. Block, 2020). According to (Balard A. J., 1834) “In 1834, French chemist Antoine Jérôme Balard discovered Hypochlorous acid (HOCl) as the infection-fighting compound found naturally in the white blood cells of the human body by adding, to a flask of chlorine gas, a dilute suspension of mercury(II) oxide in water. It has been used in the medical field for over a century. Before antibiotics were available, HOCl was used to irrigate and disinfect wounds in World War I”.

Hypochlorous acid (HOCl) is the best available chlorine-based disinfectant and very effective in disinfection. Most of the people never heard of it, but HOCl produced in their body by white blood cells in immune system. Also, HOCl produced by salt, water and electricity in electrolytic cells (types of electrochemical cells), which an industrial technology. Sodium hypochlorite (Bleach) is another chlorine-based disinfectant and it is very harmful, unlike hypochlorous acid. Hypochlorous acid is 70 to 120 times more effective at killing pathogens and bacteria, also one hundred percent safe for human and non-irritant. All of concentrated sanitizer can be dangerous and hypochlorous acid is no exception due this fact. So, it should use at lower chlorine concentration than 500 [ppm] (Site F. o.).

According to (Site K.) and (K. Whangchai), “Hypochlorous acid also called by Electrolyzed Water (EW), the concept of Electrolyzed water (EW) was originally developed in Russia, where it has been used for water decontamination, water regeneration and disinfection in medical institutions. Since the 1980s, EW also has been used in Japan. One of the first applications of EW was the sterilization of medical instruments in hospitals. Later, it was utilized in various fields, such as agriculture or livestock management, but the use of EW has been restricted by its short shelf life. With recent improvements in technology and the availability of better equipment, EW has gained popularity as a disinfectant in the food industry”.

1.1 Motivations

The hypochlorous acid is highly efficient disinfection solution. In electrolysis system, hypochlorous acid produced by water, NaCl salt and electricity. So, it is very cost-effective disinfectant. This important issue has led to the writing of this report on the production of hypochlorous acid through electrolysis. Also, by using this technology for producing hypochlorous acid, disinfectants with the lowest possible cost can be produced industrially. In this situation, human beings are really need to hypochlorous acid as a disinfectant. Also, many disinfectants are harmful to skin and body of humans but hypochlorous acid is completely safe for humans, even it can be sprayed in the mouth to oral disinfection.

1.2 Objectives

The aim of this project is evaluating four different models of electrolytic cells for producing the hypochlorous acid and identify their advantages and disadvantages and finally recommend the best available system for the producing of HOCl according to the advantages of it. Also, an economic review of the electrolytic cells that produce hypochlorous acid has been written because economic issues are one of the most important aspects of investing.

1.3 Methodology

The methodology of this project is literature review (Techno-economic review) and has several chapters:

- Chapter 1 is first chapter and about introduction.
- Chapter 2 is about hypochlorous acid, how could produce it, stability of it and applications of it.
- Chapter 3 is about electrolysis system, electrolytic cells and parts of electrolytic cells.
- Chapter 4 is main chapter of this report and about literature review, basic design of cells for producing hypochlorous acid and advantages and disadvantages for each type.
- Chapter 5 is about quality criteria for feed materials, such as quality of water and quality of salt.
- Chapter 6 is about quality criteria and maintenance for electrolysis systems parts, such as cell body, electrodes and control system.
- Chapter 7 is second main parts of this thesis and about economic review and considerations.
- Chapter 8 is about conclusion and summery of all of the final report.
- Chapter 9 is about recommendations for future works.
- Chapter 10 is about references.
- Chapter 11 is last chapter and about appendices.

1.4 Expected Outcomes of Thesis

Hypochlorous acid is widely used in the disinfection process. finding the ways that produces hypochlorous acid efficiently and evaluating advantages and disadvantages of each system can helps to everyone. Also, gathering this information can be start a project for a student in the pharmacy field about illness and disinfection subjects. During my studies, I found out that HOCl heals bed sores and it helps eye treatment from diseases and shortness of breath and all kinds of colds. The applications of hypochlorous acid briefly will be studied in second chapter. However, gathering this information can be a guideline for constructing and purchasing these devices because useful information about these electrolytic cells is readily available in this report, such as operating conditions, quality criteria and maintenance, feed quality, descriptions of each model of electrolytic cells and contact information of many hypochlorous acid suppliers, etc.

Hint: It is important issue, I using APA style for referencing in Word Microsoft Office.

Chapter Two

Hypochlorous Acid and Its Applications

CHAPTER 2 - HYPOCHLOROUS ACID AND ITS APPLICATIONS

2.1 What is Hypochlorous Acid

According to (Sansebastiano, 2006), (Michael S. Block, 2020), “Hypochlorous acid is a weak unstable acid that naturally forms when chlorine dissolves in water and itself partially dissociates, forming hypochlorite, HOCl and OCl^- are oxidizers, and the primary disinfection agents of chlorine solutions. Furthermore, it cannot be isolated from these solutions due to the rapid equilibrium with its precursor. Also, it is a participant of reactive oxygen species and a chlorine oxoacid and a conjugate acid of hypochlorite. Its chemical formula is HOCl, its molar mass is 52.46 [gr/mol]. In addition, it is a simple molecule with oxygen in the center which connects with the chlorine and hydrogen atoms through a single bond. Besides, in the common representation we can write its chemical structure as shown in the image below:

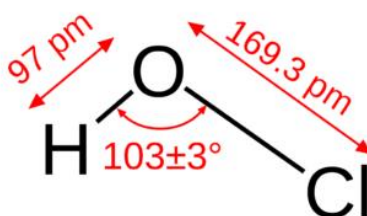


Figure 1 - 2.1 - Chemical Structure for Hypochlorous Acid

It only exists as an aqueous solution. In addition, it is a colorless solution, and telling its precise physical properties is difficult, as they depend on how to concentrate the solution is. Dry or anhydrous hypochlorous acid is impossible to prepare since the molecule exists in equilibrium with its anhydride”.

Table 1 - 2.1 - Properties of Hypochlorous Acid

CAS Name	Hypochlorous acid
CAS Registry Number	7790-92-3
Formula	HOCl
Structure	Cl—OH
Molecular weight	52.46 g/mol
Water solubility	Soluble
Comment	The primary active species in solution. Present at not more than 60 ppm.

Hypochlorous acid exists in a wide range of chlorine concentration, its effectiveness depends on its chlorine concentration, for example, it is virucidal at chlorine concentration above 50 [ppm], HOCl is very effective against a low-pathogenic avian influenza virus (AIV), spraying HOCl with 50, 100, 200 [ppm] at pH 6 decreased avian influenza virus within 5 seconds. In 50 [ppm] chlorine concentration, solution could be effective after spraying at a distance of 30 cm. In another case, when HOCl solutions were sprayed directly onto AIV within 10 seconds, the solutions of 100 and 200 [ppm] inactivated AIV immediately but 50 [ppm] solution required at least 3 minutes of contact time (Hakimullah Hakim, 2014) and (Dr.Sohrabi, 2020).

HOCl is an oxidizer agent and each oxidizer agent have ORP (Oxidation-Reduction Potential), it indicates whether it can be effective against the virus or not. Oxidation-Reduction Potential measured by millivolts [mV], it is the potential of a sanitizer in killing bacteria. The bacterial effect of hypochlorous acid against a wide range of various bacteria and pathogens depends on ORP of it and amount of free available chlorine (FAC) concentration on it. Higher ORP means hypochlorous acid can easier destroy the microorganisms and bacteria. Also, ORP depends on free chlorine concentration and pH level. Higher FAC and lower pH level of hypochlorous acid will have higher ORP (Patent, Apr 28, 2014), (Instruments, March 12, 2018).

According to (TREVOR V. SUSLOW) , “Research has shown that at an ORP value of 650 to 700 [mV], free-floating decay and spoilage bacteria as well as pathogenic bacteria, such as E. coli O157:H7 or Salmonella species are killed within 30 seconds”, so if oxidizing agents have higher ORP value than 700 [mV], it could kill bacteria and viruses within 30 seconds.

In this project the generation of hypochlorous acid by electrolysis of water, salt and in some cases using vinegar or any safe acid or HCl will be studied. In electrolytic cell, when DC current is applied, electrochemical processes at the material electrode surface transform the brine solution into an activated ‘metastable’ state and hypochlorous acid will be produced. Also, this acid is generated by different ways, these ways are as follows:

1. hypochlorous acid could be generated by adding chlorine into water, then it gives hypochlorous acid together with hydrochloric acid (HCl): $\text{Cl}_2 + \text{H}_2\text{O} \rightarrow \text{HOCl} + \text{HCl}$, these products are very unstable.
2. Stable hypochlorous acid could be produced by dissolving chlorine gas into the sodium hydroxide solution (Fair, 1948).
3. HOCl could be generated by dissolving dichlorine monoxide in water: $\text{Cl}_2\text{O} + \text{H}_2\text{O} \rightarrow 2\text{HOCl}$.
4. The hypochlorous acid could be generated by reverse reaction of sodium hypochlorite and hydrogen peroxide (Egon Wiberg).
5. Recently, two companies have made some tablets that can be dissolved in 10 liters of water, then hypochlorous acid is produced. It is interesting to know that according to their documents, these tablets do not rot for years and retain their properties. These companies did not respond to my email and I did not find more information about them in their sites, I have mentioned the names of the these companies in the appendix A and "tablet" is written in parentheses in front of the company name (A Burton & Sons cc (2009/231032/23) T/A), etc.

2.2 pH Effect on Hypochlorous Acid

The form of free available chlorine in hypochlorous acid depends on the pH level, there are existed four forums of free available chlorine in various pH levels in an equilibrium: chlorine gas, hypochlorous acid and hypochlorite ion (OCl^-) and sodium hypochlorite (NaOCl). According to figure 2.2, In constant temperature of 25 [°C], when the pH is below 1.5, free chlorine solution existed as chlorine gas. When the pH is between 1.5 to 7.5, the free chlorine solution existed as hypochlorous acid. When the pH is above 7.5, free chlorine solution existed as hypochlorite ion (OCl^-) and sodium hypochlorite (NaOCl). Also, when pH is 5, nearly all the chlorine solution is present as hypochlorous acid. In the range of 2 to 7 for pH, more than 70% of the solution is hypochlorous acid. If the pH level of solution rises above 7 or it decreases lower than 2, the volatility of hypochlorous acid increases and its shelf life is reduced. If hypochlorous acid with more stability and higher shelf life is needed, pH level must be controlled in this range (Emlen Way), (G. Rossi-Fedele, 2011 Macmillan Publishers Limited) and (Group c. , 2013).

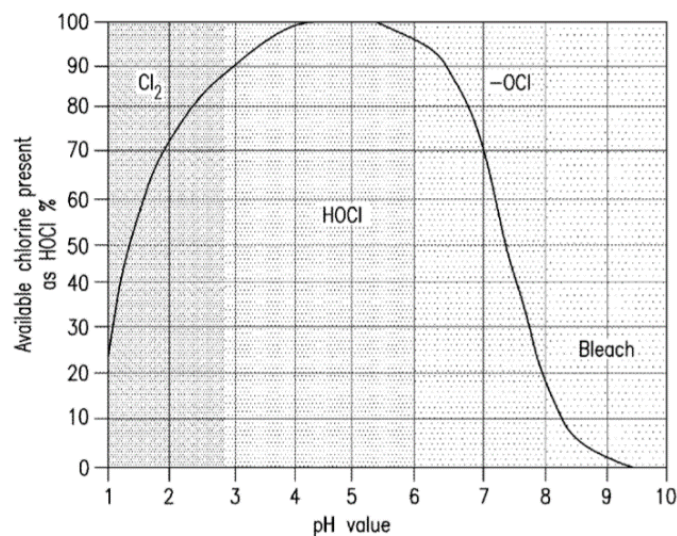


Figure 2 - 2.2 -The Effect of pH on Available Chlorine Present

Since there are different forms of free available chlorine in different pH levels, a solution of all these forums is existed in different pH levels. However, if pH is between 2 and 7, the higher the amount of hypochlorous acid is existed in solution, which is called hypochlorous acid solution. Antimicrobial effects of hypochlorous acid (HOCl) are much greater than hypochlorite ion (OCl^-). So, chlorination at low pH is more effective disinfection because HOCl is existed rather than OCl^- at low pH levels. At high pH levels, OCl^- existed rather than HOCl , which reduces disinfection efficiency (Site C. o., About Category) and (Site B.).

According to figure 2.3, when pH level is 4, only the hypochlorous acid existed in the solution. By increasing pH levels, the amount of hypochlorous acid decreases and the amount of hypochlorite ion increases. At pH 7.5, the amount of the HOCl and OCl^- is equal in solution. When pH level is above 7.5, the amount of hypochlorite ion is higher than hypochlorous acid and finally at pH of 11, there is no hypochlorous acid in solution. The pH level is a very important factor in the production of hypochlorous acid and has effect on Free available chlorine concentration and ORP. In Chapter 5.3, the strategies for controlling pH in the specific range will be studied.

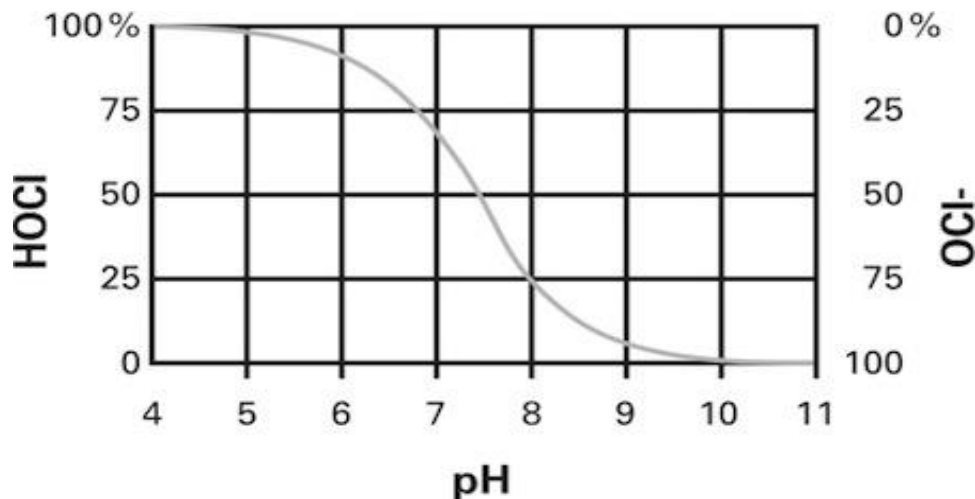


Figure 3 - 2.3 - Chlorine pH Scale for HOCl and OCl⁻ in higher pH level than 4

2.3 Stability of Hypochlorous Acid

Several parameters affect to stability and shelf life of hypochlorous acid, such as pH, ORP, salinity and FAC (free available chlorine). HOCl have a limited shelf life, its shelf life can be few day or few month and depends on these parameters that mentioned above. Also, quality of feed is very important factor and it could increase the shelf life of HOCl solution. Higher quality of water can be increasing the shelf life of HOCl, so when used purified water as feed, shelf life of HOCl increases. HOCl is more stable at low pH levels, so acidification of electrolyte solution by some safe acid could be useful for increasing shelf life of HOCl (Patent, Apr 28, 2014), (Michael S. Block, 2020) and (Group A. , 2020).

HOCl does not stay active for a long time, so it is necessary to know how it is stored. Hypochlorous acid has a partial dissociation in water and the dissociation constant (K_a) of it is 3×10^{-8} at 25 [°C]. This dissociation constant is relatively high and to prevent the dissociation of HOCl, type of packaging and storing must be specific. According to (Michael S. Block, 2020), “Rossi-Fedele et al investigated the shelf life of HOCl by being either exposed to or protected from sunlight. When the HOCl solution was exposed to sunlight, the chlorine reduction started on day 4. When it was sheltered from sunlight, the chlorine reduction started after day 14. The half-life increases with decreasing pH owing to the decreasing ratio of OCl⁻ to HOCl. The parts per million (ppm) is the concentration of the OCl⁻, which is the active ingredient and is known as the available free chlorine (AFC) in the solution. HOCl solutions are less stable when exposed to UV radiation, sunlight, or contact with air”. So, the materials must be chosen for the packaging that block the sunlight, such as opaque PET bottles, and also use a standard cap for bottle to minimized the contact with air. Also, hypochlorous acid solutions should be stored in dark and cool places like a refrigerator (Patent, Apr 28, 2014) and (G. Rossi-Fedele, 2011 Macmillan Publishers Limited).

2.4 Some Applications of Hypochlorous Acid

In this section, some applications of hypochlorous acid discussed, HOCl has a wide range of applications in different industries. The dosage (the amount of free available chlorine concentration in water) of hypochlorous acid is various in different applications. As mentioned, high concentrations of chlorine in HOCl could be dangerous and cause some problems like the other concentrated sanitizer solutions. Some applications of hypochlorous acid are as follows:

- It is a powerful weapon against all bacterial, viral, and fungal human pathogens, it could destroy 99.9999 percent of bacteria and germs, such as E.coli, staphylococci bacteria and Corona virus, etc (Khaldoon A. Mourad, 2019).
- **Agriculture sanitization:** It can remove bacteria and microbes on fruits and vegetables.
- **Live stock sanitization:** It can sterilize the farm by ultrasonic fogging sanitizer and also prevent many kinds of disease of horses and cows, etc.
- **Meat sanitization:** It can remove bad odor of meat effectively in many places, such as restaurant, feeding facilities, kitchens, restrooms, floors and drains and also it can be used to cleaning the chicken meat, fish meat and red meat.
- **Food sanitization:** It can be used for food treating and prevent to food poisoning, also It can be used as ice in food sanitization for sea food (Fera R. Dewi, 2017 March 10).
- **Hospital cleaning:** It can prevent to hospital infection and use for cleaning hospital zone.
- **School sanitization:** It can disinfect the school environment outdoor and indoor and classrooms.
- **The medical field disinfection:** It used for washing and treating all kinds of wounds, such as deep wounds, bed sores and infectious wounds, etc. Also used for eye care and eye treatment.
- **Home sanitization:** It can be replaced with deodorizes, bleach, kitchen cleaner, glass and rug cleaner and it is more efficient than bleach and completely safe for human and pet body.
- **Swimming pools sanitization:** It can be used for cleaning the swimming pools.
- **Fogging:** It can disinfect the indoor places by ultrasonic fogger, also breathing HOCl fog can heals shortness of breath (John Ware, 2020).
- **Hand Sanitization:** It can use for hand sanitizing, hand antiseptics and It does not irritation to eyes and skin like alcohol (Site H. a.).
- **Mouth and Teeth disinfection :** It can be used for mouth and teeth disinfecting because it is completely safe for human body.
- **Surface Sanitization:** It can use for surface cleaning But in high concentrations, it causes corrosion of metals after a while (Michael S. Block, 2020).
- **Manufacturing Cleaning:** It can remove biofilm and scale from manufacturing equipment and it is not flammable.
- **Water disinfection:** It can remove all pathogens and viruses from water.

Higher free available chlorine concentration could increase the rate of disinfection but FAC concentration higher than 500 [ppm] could be dangerous for human body. According to (Dr.Sohrabi, 2020), the required FAC concentrations for disinfection are recommended. These required FAC concentrations are as follows:

Hint: Time for contacting between HOCl and virus is also an important factor, but in this paper did not mention the time require for cleaning with this required FAC concentration.

- HOCl specifically used for water disinfection is effective at 1 to 2 [ppm], also EPA allowed to use 4 [ppm] in this case.
- HOCl specifically used for surface cleaning is effective at 30 [ppm], also FDA allowed to use 200 [ppm] in this case.
- HOCl specifically used for metallic surface cleaning is effective at chlorine concentration lower than 200 [ppm].
- HOCl specifically used for fruits and vegetables sanitizing is effective at chlorine concentration lower than 70 [ppm].
- HOCl specifically used for toothbrushes and towels cleaning is effective at 70 [ppm].
- HOCl specifically used for hand sanitizing is effective at 100 to 200 [ppm].
- HOCl specifically used for the floor of indoor places disinfecting is effective at 200 [ppm].

Chapter Three

Electrochemistry and Electrolysis Systems

CHAPTER 3 - ELECTROCHEMISTRY AND ELECTROLYSIS SYSTEMS

3.1 Electrochemistry

According to (Site W. P.), “Electrochemistry is the branch of physical chemistry that studies the relationship between electricity, as a measurable and quantitative phenomenon, and identifiable chemical change, with either electricity considered an outcome of a particular chemical change or vice versa. These reactions involve electric charges moving between electrodes and an electrolyte (or ionic species in a solution). Thus, electrochemistry deals with the interaction between electrical energy and chemical change”. Also, these reactions are performed in two different types of electrochemical cells, the first type is called electrolytic cell and the reaction is performed non-spontaneously because Gibbs free energy for these reactions (redox) is higher than zero ($\Delta G > 0$) and consumes electrical energy, the second type is called galvanic cell and these reactions (redox) occur spontaneously because Gibbs free energy of these reactions is lower than zero ($\Delta G < 0$) and electricity is generated. To produce the hypochlorous acid, redox reactions is performed non-spontaneously and electrolytic cell type will be used (Libretexts, Aug 15, 2020; Libretexts, Aug 15, 2020) and (Scott, 2019).

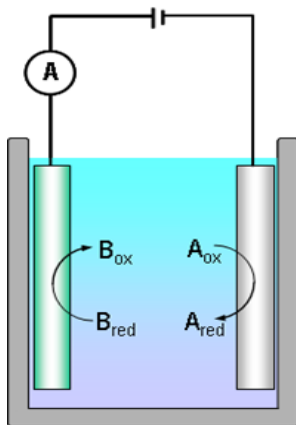


Figure 4 - 3.1 - Scheme of Electrochemical Cell

3.2 Electrolytic Cell Systems

In electrolytic cell systems, the important factor is interchange of ions and atoms by addition or removal of electrons from the external circuit. An Electrolytic cell system has several components that will be discussed in the next part. In general, an electrolysis system is the chamber which the reductions and oxidation reactions occur in it. In chemistry, the loss of electrons is called oxidation reaction and the gain of electrons is called reduction reaction. So, to perform these reactions in an electrolytic cell, two conductive metals are needed for electrodes which are anode and cathode, an electric DC current power supply and an electrolyte solution. Cathode is negative electrode, it attracts positive ions and anode is positive electrode, it attracts negative ions. When DC current power supply is connected to the electrodes, positive ions (cations) move toward the electron-providing cathode and negative ions (anions) move towards the electron-extracting anode. All positive and negative ions are

existed in electrolyte which is conductive ionic solution. Reduction reaction occurs at the cathode and oxidation occurs at the anode. This means that the anode must be coated to prevent the corrosion. To better remember this fact, The term “red cat” can be useful that means reduction occurs at the cathode (Site B. C.), (KIRJA-CHEM-E4185, 25.02.2019-29.05.2019), (CEE 597T, 2019), (Faraday, 1849), (Kotz, 2012), (Chemistry) and (Site C. o., About Category).

According to (Site B. C.), “A higher current flow (amperage) through the cell means it will be passing more electrons through it at any given time. This means a faster rate of reduction at the cathode and a faster rate of oxidation at the anode. This corresponds to a greater number of moles of product. The amount of current that passes depends on the conductance of the electrodes and electrolyte, though it also depends on how much current the power source itself can generate. A higher potential difference (voltage) applied to the cell means the cathode will have more energy to bring about reduction, and the anode will have more energy to bring about oxidation. Higher potential difference enables the electrolytic cell to oxidize or reduce energetically more difficult compounds. This can drastically change what products will form in a given experiment”. In electrolysis system, there are six principal variables (Site I.-I. , 2020) and (Analysis):

1. Composition of electrodes
2. Electrolyte properties, such as pH level and conductivity, etc.
3. Voltage and current levels of DC supply power
4. Temperature of the electrolytic cell
5. Time duration of the reaction
6. Divider between electrodes

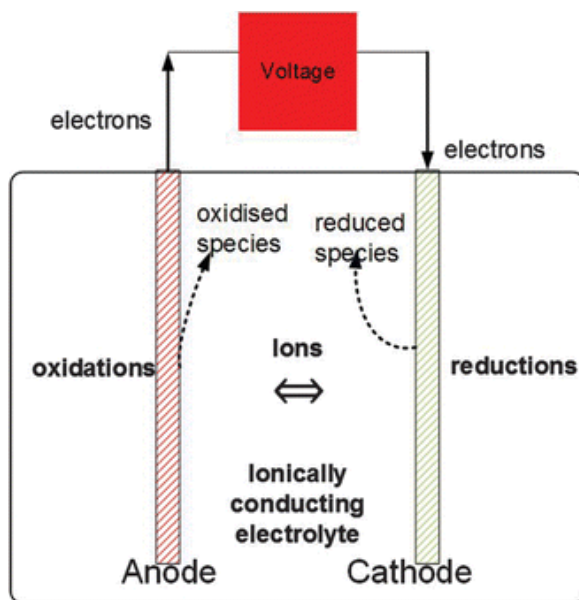


Figure 5 - 3.2 - Schematic of Electrolytic Cell

3.2 Main Components of An Electrolytic Cell

3.2.1 Power Source (Direct Current (DC) Supply)

In electrolytic cells, a direct current (DC) power source is needed to provide the electrical driving force (potential difference) for the electrons to move between the electrodes. The direction of current is always from the positive pole to the negative pole in the DC power supply but in alternative current (AC) power supply, the direction of the current is constantly changing because its sinusoidal waveform of voltage. A direct current power source is used because the location of electrode does not change and the direction of current must be constant. There are two direct power for electrolysis system, which are batteries and AC converter to DC power supply. Many types of batteries used in electrolysis system, such as zinc-manganese batteries, mercury batteries, the lead-acid batteries (rechargeable) and lithium batteries, etc (Faraday, 1849), (Chemistry) and (Bier, 2018).

3.2.2 Cell

The reactor contains electrolyte and two or more electrodes, an electrolyte solution and a separator. In electrolytic cells, oxidation and reduction reactions occurred by using direct current power supply. The material of body of cell must be corrosion resistant because the electrolyte could corrode body of the cell. Also, the material of body of the cell must be non-conductive, such as plastic and glass, etc. one of the common materials for body of the cell is ABS.

3.2.3 Electrolyte

Electrolyte solution is the conductive solution that carry electric current and containing many free ions, it is responsible for carrying the electric current in electrolysis process. The cations migrate to the negative electrode (cathode) and the anions migrate to positive electrode (anode) inside the electrolyte. Electrolyte solution, such as acids, bases and salts. In the hypochlorous acid production process, the electrolyte is a solution of water and salt (brine) (Bier, 2018) and (Chemistry).

3.2.4 Electrodes

Electrodes are electrical conductor metal that connected to the battery terminals and are located inside the electrolyte. there are two types of electrodes, the electrode that is connected to the positive pole of the battery and attracts negative ions (anions) is called the anode, and the electrode that is connected to the negative pole of the battery and attracts the positive ions (cations) is called the cathode. As mentioned above, at the anode (positively charged electrode); oxidation reactions (loss of electrons) occurs and reduction reactions (gain of electrons) occurs at the cathode (negatively charged electrodes). Two baffles are used to hold electrodes in their positions and adjusting the right distance between them and also these baffles cause disturbance in the electrolytic cell. Also, spacing between electrodes and their configurations are very important factors for electrolysis system (Chemistry), (Faraday, 1849), (Site E. 3.), (Libertysprayers) and (Frank X. Galneder, 1974).

The material of electrodes is a very important factor. The efficiency of electrodes depends on chemical reactivity between electrolyte and electrodes, conductivity and resistance of electrodes and manufacturing cost. At the anode; the oxidation reactions occurs and also corrosion happens in the anode, so a material for the anode is needed that has least reactivity and takes a longer time to corrode the anode (Libretexts, Aug 15, 2020) and (Libretexts, Aug 15, 2020). There are many parameters in choosing the right material for the electrode, such as corrosion in the anode, high conductivity, low

electrical resistance and high resistance in aqueous solution, etc. There are several different materials for electrodes. Some of these are as follows (Site E. 3.) and (Analysis):

- **Carbon and graphite**
Carbon and graphite are non-metallic electrodes and are used in various electrodes applications. They resistant in high temperature and have low cost.
- **Mercury**
This type of electrode is very popular because it is reproducible and renewable. Also, it is very toxic and very harmful to the skin.
- **Nanomaterial-based**
This type of electrode is semiconductor and has high surface area for increasing the level of oxidation and reduction reactions. Metal nanomaterials, such as gold nanoparticles, carbon nanotubes (CNTs), metallic oxide/sulfide nanomaterials and graphene are very popular nanomaterials for electrode.
- **Chemically modified**
Chemically modified electrodes are conductive or semiconductive electrodes coated with monomolecular, multi-molecular, ionic, or polymeric film to achieve specific properties of simple electrode materials.
- **Noble metals**
Noble metals electrodes are very conductive and have low resistance, such as gold, platinum and silver and have a wide range of applications.
- **Silver**
“Silver has the highest conductivity of all metals”. Also, it has low resistance. Fine silver is silver with 99.99 percent purity. Pure and fine silver has a wide range of applications and used for silver-based alloys.
- **Copper**
“Copper is second only to silver in terms of bulk electrical conductivity. It is also used in alloys with graphite, tellurium, and tungsten, and is used to make brass and bronze”. In addition to high conductivity and low resistance, copper also has high flexibility.
- **Titanium**
Titanium electrodes are very good corrosion resistance electrode and also are non-ferrous metal for electrodes.
- **Brass**
Brass is an alloy of zinc and copper. It has lower conductivity than copper.
- **Platinum and palladium**
“Platinum forms useful alloys with iridium, ruthenium, and tungsten. Palladium forms useful alloys with copper and ruthenium”. these materials have high conductivity and low resistance. Also, have high corrosion resistance and it useful for anodes. Cost of these material is very high and They are mostly used for coating means another electrode material used as core of electrode and platinum and palladium coating on core of electrode.
- **Mixed metal oxide (MMO)**
One of the common type of electrodes and typically used for anode. These electrodes have an oxide coating for corrosion protection, this coat is mixed of ruthenium, iridium and platinum. The core metals are zirconium, tantalum and titanium (most common). This type of electrodes mostly used in hypochlorous acid generators.

<u>Material</u>	<u>Advantages</u>	<u>Limitations</u>
Pt	available wire, flat plate & tube large range of sizes Pt-Rh alloy for rigidity	low hydrogen overvoltage so cathodic potential range limited expensive
Au	configurations same as Pt larger cathodic potential range	larger cathodic potential range anodic window limited by surface oxidation expensive
Carbon	many types and configurations good cathodic potential range	quality varies greatly hard to shape
C-paste	wide potential range low background current inexpensive	unstable in flow cells cannot use in organic solvents
Hg	excellent cathodic window easy to "refresh" forms amalgams	limited anodic window due to mercury oxidation toxic

Figure 6 - 3.3 - Some Materials for Electrode and Their Advantages and Limitations

In the following, two important factors of electrodes will be reviewed:

1. Spacing Between Electrodes

Spacing between electrodes is very important factor in electrochemical cells. The energy consumption of the system can be optimized by changing this distance. Efficient spacing between electrode depends on some parameters, such as material for electrodes, conductivity of electrodes, electrical resistance of electrodes, conductivity and resistance of electrolyte. According to (Faulkner), "This is mainly a problem for electrolytes with low conductivity or where the currents flowing are very high. Thus, by increasing the distance between the electrodes, the resistance in the electrolyte will increase, and it is better to have electrodes close together. The resistance will contribute to the overall potential according to Ohm's law, Voltage = Current $\times$ Resistance ($V = IR$)". Therefore, we can be improved the efficiency of the system by reducing the resistance or using smaller electrodes that have a lower overall current at a given potential and also can decrease the space between electrodes (Group C. S.) and (Faraday, 1849).

2. Monopolar or Bipolar Configuration

In the electrochemical cells, the electrode connection has effect on the energy consumption and also Plurality of each electrode configurations are different. There are two common types of electrode configuration, bipolar and monopolar. If system electrodes arranged by bipolar configuration, plurality of electrochemical cells are electrically connected in series, the electrodes arrangement is as follows; cathode - anode - cathode - anode - cathode. If system electrodes arranged by monopolar configuration, the electrodes are connected in parallel, the electrodes arrangement is as follows; cathode, anode, cathode, anode, cathode (Thorben Muddemann, Received: August 28, 2019; accepted: August 29, 2019) and (Nishiki, Isao Sawamoto, Shuji Nakamatsu, & Takayuki Shimamune, 1991).

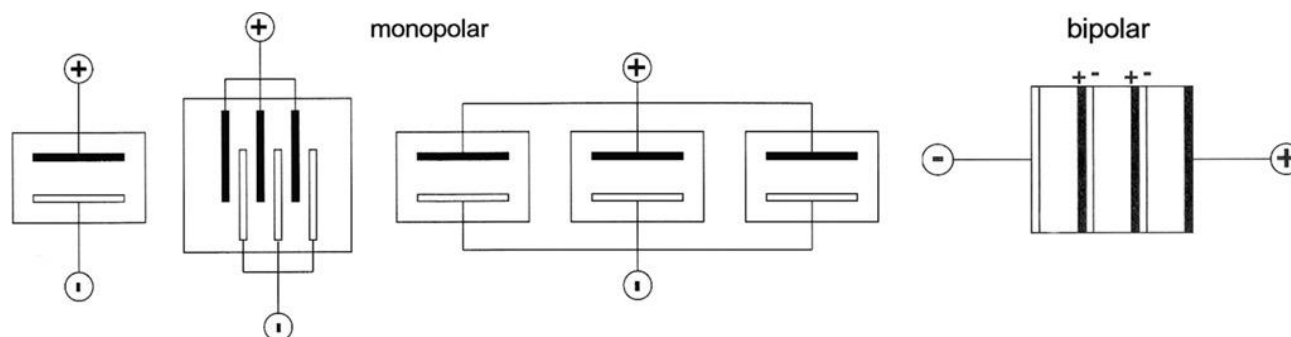
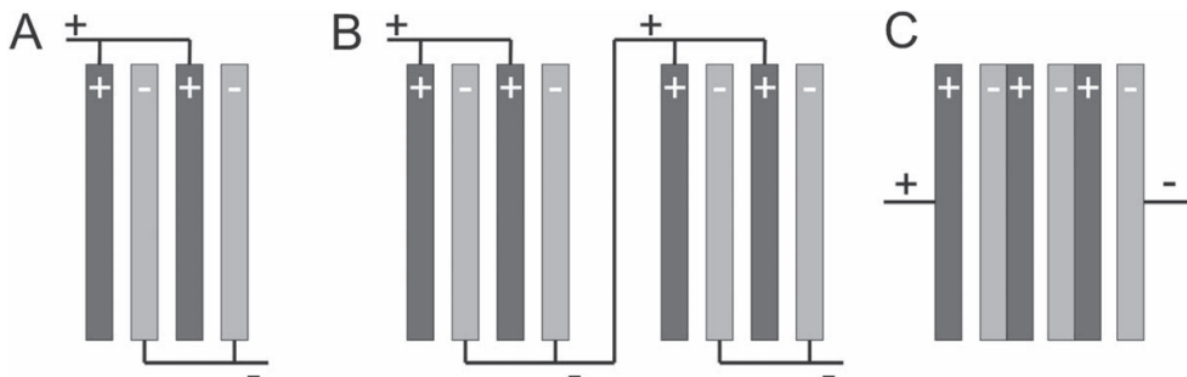


Figure 7 - 3.4 - Chart for Monopolar and bipolar Electrodes Configurations

According to (Samuel C. Perry, 2020), “Monopolar connection as is shown in figure 3.5. A, where each electrode is either positive or negative. This arrangement maintains the cell voltage of one individual cell but is able to generate high currents. In order to increase the voltage, the monopolar connected cells can be arranged in series, see figure 3.5. B. Another strategy consists of connecting the cells in a bipolar configuration as is shown in figure 3.5. C, which is commonly used in electrosynthesis cells, fuel cells and redox flow batteries. In this arrangement the voltage depends on the number of cells”. In monopolar configuration, the larger current needed and according to ohm’s law, amount of applied voltages are smaller than bipolar for same electrodes and cell size. The current is uniformly distributed to electrochemical cell in bipolar configuration but it is not always uniformly distributed in monopolar configuration.



(A) monopolar electrode connections, (B) monopolar cell stacks connected in electrical series, (C) bipolar electrodes.³⁴

Figure 8 - 3.5 - Monopolar or Bipolar Electrodes Configurations

Chapter Four

Technology Review

CHAPTER 4 - TECHNOLOGY REVIEW - ELECTROLYTIC SYSTEMS FOR THE PRODUCTION OF HYPOCHLOROUS ACID

4.1 Technology Classification

The key of hypochlorous acid production is electrolysis process and it has made progress over the recent decades. The development of electrolytic cells for producing hypochlorous acid became a great innovative breakthrough in the 1970s. According to these improvement in electrolytic cell can generate a stable solution of hypochlorous acid. There are four different models of electrolytic cells for producing the hypochlorous acid From the past to the present and each of the models has specific advantages and also disadvantages which will be reviewed in the basic design part (4.2). The product (hypochlorous acid solution) of each the models has different chemical properties because hypochlorous acid existed in a wide range of free available chlorine concentration and each model produces hypochlorous acid solution in different operating conditions. Also, there are two main feed for these cells: water and salt (brine solution), water and Hydrochloric acid (HCl). In this field, japan is one the best manufacturers of hypochlorous acid generators (Site H. a.), (Site B. C.), (Faraday, 1849), (Site C. o., about category), (WANG, 2011), (Tian Ding, 2019) and (Technologies, 2015).

As mentioned above, The chemical and physical properties and composition of hypochlorous acid will vary depending on the concentration of brine solution, pH level, voltage, current density, temperature of electrolyte, time of electrolysis and mode of electrolysis operating, etc. Antimicrobial and sanitizing effect of hypochlorous acid depends on these parameters. Amount of current density has effect on efficiency of the electrolytic cells. Current density is very important factor in electrolysis system and effective current density is defined by this equation:

Effective Current Density = Current / true area of the electrode.

According figure 4.1, increasing the density of DC current could increase the free available chlorine concentration in the hypochlorous acid solution (Technical Evaluation Report, August 13, 2015) and (V.M. Bakhir, From the middle of 2012 “Delfin Aqua” ltd).

K.A. Mourad, S. Hobro / Science of the Total Environment 709 (2020) 136108

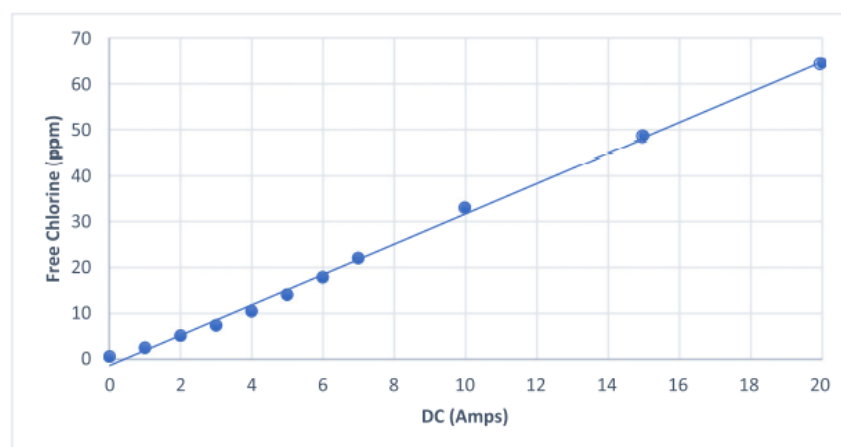


Figure 9 - 4.1 - Free Chlorine Concentration Under Different DC Amps

These electrolytic cells could operate in two types of process, continuous and batch process. The batch process is the process which the feed is placed inside the electrolytic cell and after a while the products are ready. Continuous process is the process which feed enters the cell at the specific flow rate and products leaves the cell at the specific flow rate. Evaluating the advantage and disadvantages of every type of process is important to determine which one would work best for you. About cost of device, continuous process devices are more expensive than the batch process devices. However, when comparing the production rate, industrially continuous devices have higher rate of production than the batch devices. So, if you need hypochlorous acid constantly, it is easier to use continuous process devices. In batch process devices, you should to wait for producing hypochlorous acid and take it out of the electrolytic cell and refill the electrolytic cell by salt, water and turn it on, but this is not happened in continuous devices, hypochlorous acid leaves the cell constantly and it stored in the storage tank. If you have fewer labors, continuous devices are better. In terms of ease of automation, batch process is relatively more difficult than the continuous process. Both continuous and batch processes are vital in the production of materials or products.



Figure 10 - 4.2 - Some of Electrolytic Cell Devices from Dr. Vitold Bakhir

(Bakhir V.M. P. A., 2018).

In electrolytic cells for producing hypochlorous acid, there are two shapes of electrodes :

1. Cylindrical electrode
2. Plate or Prismatic electrode

Cylindrical shapes are inherently more stable than flat plates of equivalent area for electrodes. If the shape of electrodes is cylindrical, electrolytic cell has higher efficiency for producing hypochlorous acid solution. In the most hypochlorous acid generator, cylindrical electrode is used. The working mechanism of the cells does not change according to the shape of the electrodes. Shape of electrodes has effect on the quality of the hypochlorous acid and energy consumption of the electrolytic cells. Therefore, each mechanism of electrolytic cells will be reviewed according to the dividers in the middle of the cells (Insight, 07/02/1975). These cells are arranged according to the time of the invention :

4.2 Basic Design of Different Electrolytic Cells

4.2.1 Undivided Cells - Simple Cells

1. Description :

This model of electrolytic cells is very simple and it is the oldest model of electrolytic cell for producing the hypochlorous acid. In 1834, French chemist Antoine Jérôme Balard discovered the hypochlorous acid, which it was used during World War I and World War II to disinfect and cleaning wounds of war Injured. These devices operate batch mostly and during my research, I did not find any models of this device that operates continuous. Batch process means, raw materials are placed inside the electrolytic cells and after a while the hypochlorous acid is ready. In this model, there is no divider between the electrodes and the product is only hypochlorous acid solution. Simple cell produces small volumes of hypochlorous acid and it operates batch. It is not an industrial model for producing HOCl. Since this model is not an industrial model, it is discussed very briefly in this report. Many companies produce this model and one of the most famous of these companies is Ecolox Tech. (Balard A. J.–3.) and (Balard A. J., 1834).

The working mechanism of these devices is very simple, the specific amount of water, sodium chloride salt and vinegar (these amounts of raw material are different for each company and depends on the device) are placed into the cell and after a while the hypochlorous acid is ready. There are the important parameters about this reaction. Residence time of contacting electrolyte with electrodes, if raw material stays in the electrolytic cell for longer time, the free available chlorine concentration increases in the hypochlorous acid. White vinegar is an acid (standard white vinegar is a clear solution generally containing 4 - 7% acetic acid and 93 - 96% water) and is added to the solution for controlling pH level because hypochlorous acid is more stable in lower pH levels. In some papers, it is said that vinegar is added at the end of the electrolysis process because it does not the reactant of the main electrolysis reaction, but in some papers, it is said that vinegar is added with water and salt (Site F. o.).

According to (Site F. o.), “When an electrical charge is passed through a salt (NaCl) solution, the sodium separates from the chloride. Chloride is negatively charged and is attracted to the positive side of the electrical charge where it bonds with oxygen and hydrogen from the water. It gets converted from Cl^- to HOCl, otherwise known as hypochlorous acid. The sodium is positive and is thus attracted to the negative charge, where it also bonds with oxygen and hydrogen and is electrochemically converted to sodium hydroxide or NaOH”. In simple cell, electrolyte contains NaCl salt, water and a pH adjuster (like vinegar, lemon juice(citric acid)) as well. It's the pH level that determines whether the solution is predominantly hypochlorous acid. Due to the presence of vinegar or lemon juice (pH adjuster), the pH level of the solution remains acidic and therefore only the hypochlorous acid solution is formed and sodium hydroxide is not formed. Sodium hydroxide is not present in acidic pH levels.

One of the most widely used examples of this model is home care device. Many companies produce simple cell for using in home, so people can produce hypochlorous acid at home. The stability of hypochlorous acid solution is very low in these devices and It is 24 to 48 hours. If you use this solution at home, you need to buy this model. For example, as a feed for one of the home care models of Ecolox Tech company, 3 [gr] of salt added to 1000 [ml] of water and 5 [ml] of white vinegar and put it into the electrolytic cell and after 8 minutes, the concentration of hypochlorous acid is between 50

and 100 [ppm], and if higher concentration of chlorine is needed, after 15 minutes, its concentration is 200 [ppm] (Eun Sang KIM., 2020).

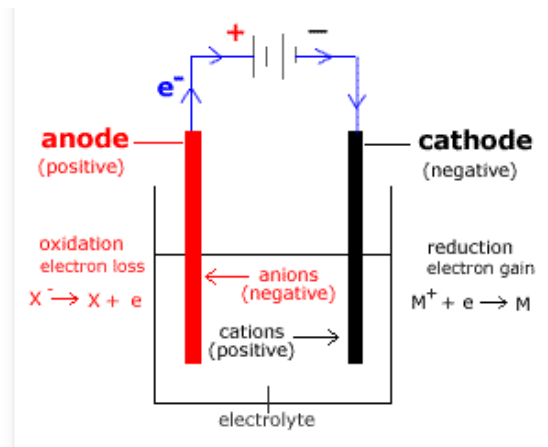


Figure 11 - 4.3 - Scheme of Simple Cell

2. Advantages of Simple Cell :

1. Batch operating
2. Simple operating mechanism
3. Controlling FAC by time indicator
4. Low electricity consumption
5. It takes up little space, small devices
6. Very practical for home care using
7. No maintenance cost
8. Cheap price
9. No installation cost
10. Feed of this apparatus is tap water and NaCl salt and some safe acid; it therefore has less adverse impact on the environment
11. Controlling pH level by vinegar or lemon juice
12. It is environment-friendly device
13. Low salt consumption
14. The weight of these devices is very low and they are portable apparatus
15. Low production cost

3. Disadvantages of Simple Cell :

1. Shelf life for hypochlorous acid from this apparatus is 24 to 48 hours
2. It Produces hypochlorous acid with very low free chlorine available concentration
3. Low efficiency for industrial use
4. This cell has one product, only produces very unstable hypochlorous acid
5. Low production capacity
6. It takes time to produce hypochlorous acid because it mostly operates batch
7. It is not an industrial device

4.2.2 Diaphragm-Divided Cells

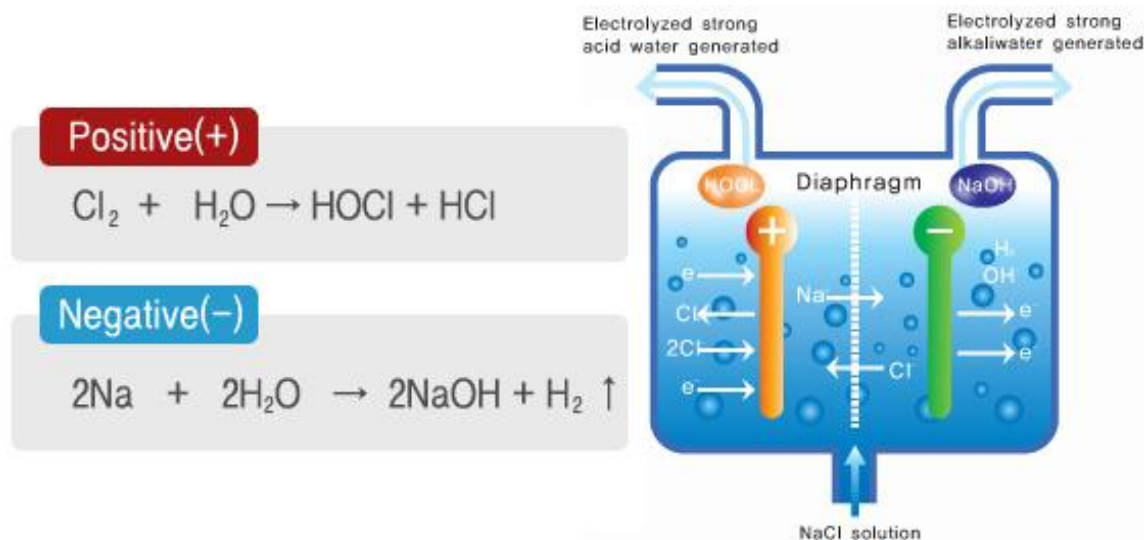


Figure 12 - 4.4 - Scheme of Diaphragm-Divided Cell

1. Description :

According to (Bakhr V.M. D. o.), “In 1989, the design of a flow-through electrochemical cell with a ceramic diaphragm was created that possessed the necessary properties of a universal electrochemical instrument. This cell provided not only an effective change in the pH and oxidation-reduction properties of various liquids flowing through the electrode chambers by direct flow or counterflow at a controlled differential pressure at the diaphragm, but also a sufficiently deep (60 - 90 %) electrochemical conversion of electrolytes in fresh and low mineralized solutions. This device was named by the authors a flow-through electrochemical modular element known as FEM-1 (UK patent GB 2 253 860). The serial production of FEM elements and electrochemical devices for various purposes was organized”. One of these various purposes is production of the hypochlorous acid efficiently. The second model of electrolytic cells that produces hypochlorous acid is the divided cells by the diaphragm. In these devices, addition to main parts of the electrolytic cell, such as cell body, electrodes, electrolyte solution and DC current power supply, a divider is located between the electrodes. A divider between electrodes could divided electrolyte into two parts: anolyte and catholyte. The electrolyte around the cathode is called the catholyte and the electrolyte around the anode is called the anolyte. The divider generally causes Na⁺ and water to accumulate around the cathode (catholyte zone) and Cl₂ and water to accumulate around the anode (anolyte zone). The anolyte contains mostly hypochlorous acid solution and the catholyte contains mostly sodium hydroxide. The feed of these devices are water and salt, without any acid for controlling the pH level. these devices operate continuously (Georgi Gluhchev, 2015), (Bakhr V.M. P. A., 2018), (Khaldoun A. Mourad, 2019), (Yu. I. Komolikov, July, 2020), (Clark, 2007 (modified June 2015)), (Reynolds, Received: 13 April 2011 /Accepted: 15 July 2011 /Published online: 2 August 2011 # Springer-Verlag 2011) and (S, February (2013)).

In these devices, the divider between the electrodes is the diaphragm. The membrane or the diaphragm is a microporous material with average pores less than one micron. The diaphragm has larger pore size than the membrane, so diaphragm has a lower efficiency than the membrane in prevent to mixing

electrolyte solutions. The diaphragm can be made by different materials, such as woven fabrics made of cloth, fiberglass, nylon, terylene, microporous rubber or microporous plastic sheets of polyethylene, polyvinyl chloride (PVC), polytetrafluoroethylene (PTFE), asbestos, aluminum, bismuth, zirconium, tantalum and titanium. However, diaphragm materials should have these characteristics: 1. Good chemical and physical stability, 2. Low electrical resistance, 3. Low cost and 4. High resistance to diffusion of electrolytes between compartments except for transport of the desired current carrying ion (S, February (2013)) and (BEER, July 23, 1963).

The divided electrolytic cell by diaphragm generally comprises an anolyte compartment containing an anode, a catholyte compartment containing a cathode. The divider between the electrodes prevents mixing the anolyte and catholyte and it could increase the quality of hypochlorous acid and also increases stability of HOCl. The pH level of catholyte and anolyte is different because different reactions performed in each fluid and there are different ions and compounds existing in each fluid. The main reaction that occurred in catholyte is: $2\text{H}_2\text{O} + 2\text{Na}^+ \rightarrow 2\text{NaOH} + \text{H}_2$ and the main reactions that occurred in anolyte is: $\text{H}_2\text{O} + \text{Cl}_2 \rightleftharpoons \text{HOCl} + \text{H}^+ + \text{Cl}^-$. In anolyte, anions (chloride and hydroxide) move to the anode and become oxygen gas (O_2), chlorine gas (Cl_2), hypochlorite ion (OCl^-), hypochlorous acid (HOCl), and hydrochloric acid (HCl). In catholyte, cations (hydrogen and sodium) move to the cathode and become hydrogen gas (H_2) and sodium hydroxide (NaOH). For example, final parameters of anolyte are the following: pH is 3.8 to 4; ORP is 1050 to 1100 [mV]; specific electrical conductivity is 3.2 - 3.5 [$\mu\text{S} / \text{cm}$] and final parameters of catholyte are the following: pH is 10 to 11; ORP is -795 to -800 [mV]; specific electrical conductivity is 4.8 - 5.6 [$\mu\text{S} / \text{cm}$] (Group A. , 2020) and (Henry W. Schussler (Harrison City, May 10, 2011)).

According to figure 4.5, When a divider existed between the electrodes in the electrolytic cell, there are two types of electrolyzed water (Tian Ding, 2019), (K Umimoto, 2013) and (Muhammad Imran AL-HAQ, Received April 6, 2005 ; Accepted June 4, 2005):

1. Anolyte or acidic electrolyzed water (AEW) is generated at the anode and contains hydrochloride, hypochlorous acid, chlorine, and oxygen gas and pH of AEW is 2.5 to 3.5, ORP is 1000 to 1200 [mV] and free available chlorine concentration is 30 to 90 [ppm]. Also, "The higher amperage and voltage result in a more acidic solution with a higher ORP and a free chlorine concentration".
2. Catholyte or alkaline electrolyzed water (AIEW) is generated at the cathode and contains sodium hydroxide and hydrogen and pH of AIEW is 10 to 13, ORP is -800 to -900 [mV]. "The indices of voltage, amperage, and flow rate settings can greatly affect the pH and ORP of alkaline EW".

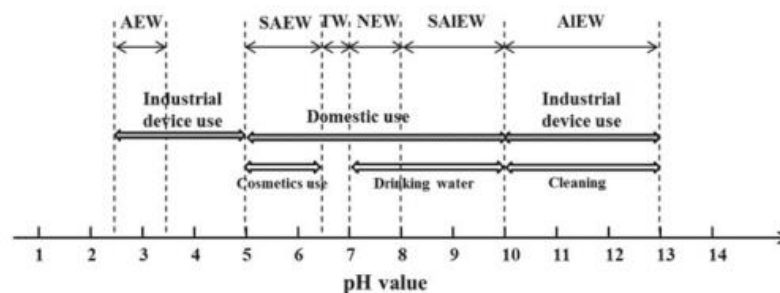


Figure 13 - 4.5 - pH Ranges of Various Electrolyzed Waters and Its Applications

Also, when electrolytic cell hasn't any divider, there are two different types of electrolyzed water depends on pH levels (Tian Ding, 2019) and (Muhammad Imran AL-HAQ, Received April 6,2005 ; Accepted June 4,2005):

1. Neutral electrolyzed water (NEW) is generated at the anode but mixed with products of cathode in single cells or simple cells without membrane or diaphragm. pH of NEW is 7 to 8, ORP is 750 to 900 [mV]. "Along with the changes in generator settings, the pH and ORP levels of neutral EW are varied, and their disinfection elements are mainly HOCl and HCl". In comparison with acidic electrolyzed water, NEW from single cell has longer shelf life under specific circumstances.
2. Slightly acidic electrolyzed water (SAEW) is generated at the anode but mixed with products of cathode in single cells or simple cells without membrane or diaphragm. pH of SAEW is 5 to 6.5, ORP is 800 to 900 [mV].

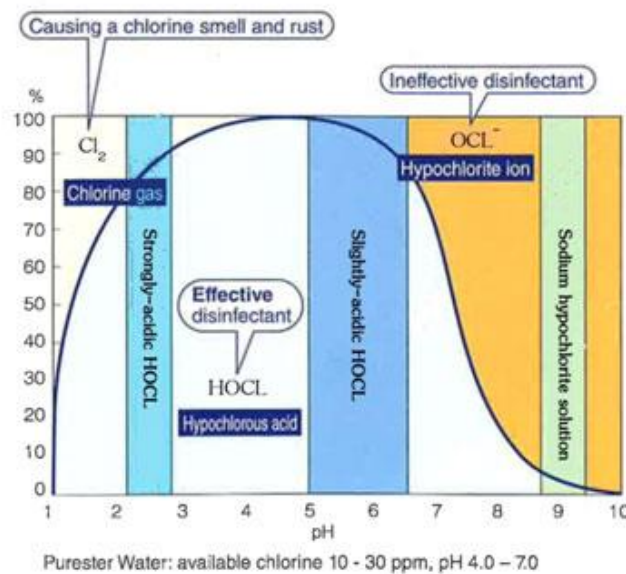
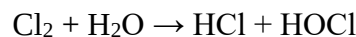
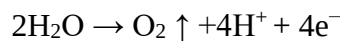
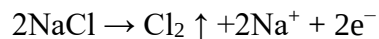


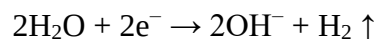
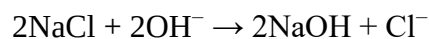
Figure 14 - 4.6 - pH Ranges of Various Chlorine-based Disinfection Solutions

In summary, the principle of generating anolyte and catholyte in divided cells by diaphragm, the reactions as follows (Tian Ding, 2019):

Equation 1 - 4.1 - Reactions in Anolyte



Equation 2 - 4.2 - Reaction in Catholyte



According to (Georgi Gluhchev, 2015), “The parameters of pH, the redox potential, ORP and the electrical conductivity of the anolyte/catholyte depend on different factors including the ratio of water volumes in the two electric chambers, the material of electrodes, NaCl concentration, the temperature, electric voltage and processing time”. As is known from previous chapters, hypochlorous acid is present in a wide range of pH levels and its stability is highly dependent on pH level and Free available chlorine concentration. These devices are controlled by pH and FAC controller because product must have specific properties for increasing its stability, the produced hypochlorous acid has shelf life some weeks and depends on storage and packing conditions; Some companies claim that their hypochlorous acid has a shelf life between 1 to 10 months. This model of these devices is an industrial model for producing hypochlorous acid and it operates continuously. In continuous process, to increase the efficiency of these device, two or more electrodes can be used as anode and two or more electrodes can be used as the cathode. Also, this model of electrolytic cells needs less labors and operators because the solution stored in the storage tank continuously. Divided cells by diaphragm are very efficient and better than simple cells for producing hypochlorous acid industrially. Many companies produce this model and the most famous of them are Aquaiox, BAKHIR & ECT, De Nora, SionTech, Envirolite, Hangzhou Meimei Technology, ProMinent, VDH Water TECH and Chlorking (Robert Guillaume, Jean-Pierre Pleska, & Jean Indeherbergh, 1981) and (Muhammad Imran AL-HAQ, Received April 6,2005 ; Accepted June 4,2005).

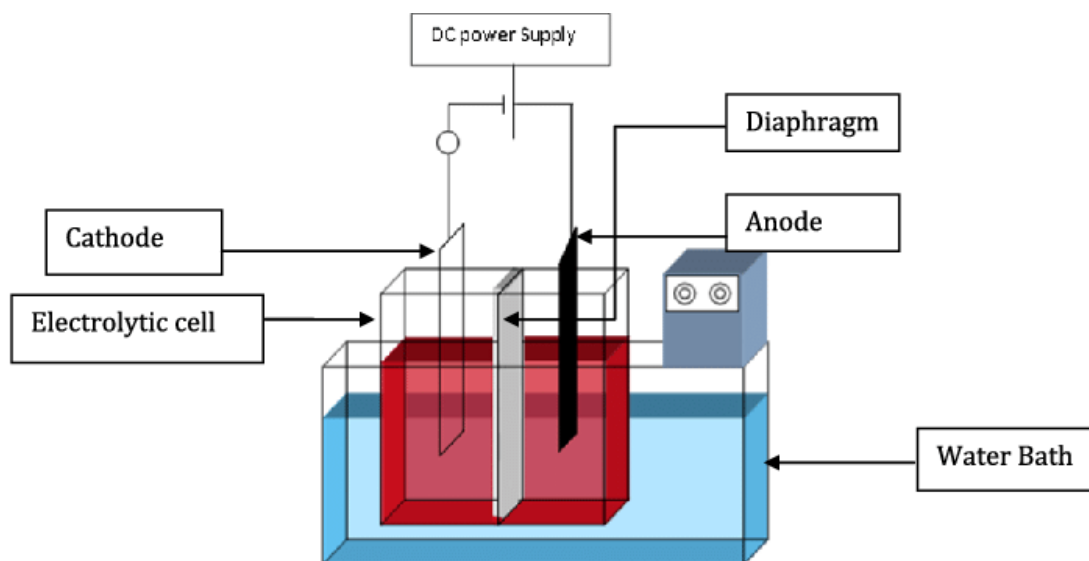


Figure 15 - 4.7 - Schematic of Electrolytic Cell with Diaphragm

These cells need to be installed because the water must enter the cell at the higher pressure than the usual water piping pressure to facilitate the moving of ions through the diaphragm. Also, Water must to be filtered before entering the divided cell by diaphragm to remove hardness from water and increasing the divider efficiency between the electrodes because these hardness from water may get stuck in the divider pores and clogs it. If the purified water used, the cell does not need to be repaired and cleaned for longer time. In Chapters 5 and 6, maintaining and cleaning cells and water purification, etc. are thoroughly reviewed. Also, if these hardness does not separate from water, the presence of these hardness, such as calcium, magnesium around the cathode will cause formation of fouling on the cathode and reduces the efficiency of the device.



Figure 16 - 4.8 - Electrolytic Cell Divided by Diaphragm

2. Advantages of Diaphragm-Divided Cell :

1. It can be operating on-site plant
2. Continuous operating
3. High production capacity
4. It produces two products, anolyte contains hypochlorous acid (HOCl) as product and Catholyte contains Sodium hydroxide (NaOH) as by-product
5. Feed of these devices is pure water with NaCl salt; it therefore has less adverse impact on the environment
6. It could produce hypochlorous acid solution with a wide range of free chlorine available concentration
7. It is environment-friendly device
8. After the initial cost of the electrolysis device, operational expenses are minimal. Thus, the use of generated hypochlorous acid is quite cost-effective
9. It has longer shelf life than simple cell, a number of vendors says shelf of hypochlorous acid from diaphragm cells is some weeks (Muhammad Imran AL-HAQ, Received April 6,2005 ; Accepted June 4,2005) (Company I.)
10. These devices have higher efficiency than simple cells
11. Less corrosion occurs in these devices
12. It has a wide range of pH; pH is controlled in the 2 to 13.
13. In addition to the main electrochemical reaction that occurs with the electrodes, the high intensity of the electric field on the surface of the electrode gives the water and its dissolved salts some electro-metastability, which increases its ORP by the order of - 800 [mV] and + 1200 [mV] respectively in the catholyte and anolyte.
14. In industrial field, it could be more efficient than simple cells and also, less labor is needed in divided cells by diaphragm

15. Long Service life because water and salt must be treated and also most of these devices use titanium electrode coated by platinum and iridium for protection from oxidation, largely increases the service life of electrolytic cell
16. It takes up space like a small cabinet

3. Disadvantages of Diaphragm-Divided Cell :

1. It has high energy consumption than simple cells and single cells
2. It used treatment salt
3. It used treatment water
4. It has installation cost
5. The price of these devices is more expensive than the simple cells
6. These devices have maintenance cost
7. It is heavier than single cells and simple cells
8. In some machines, if the pH is set lower than 5, chlorine gas is produced in addition to other species of free chlorine available (e.g. HOCl and OCl⁻ ions). In such cases, the operator must protect himself from chlorine fumes. Otherwise, these devices are safe for the environment as well as for the operator.
9. The initial purchase of the device, pump, pipe and fittings may be costly (Muhammad Imran AL-HAQ, Received April 6,2005 ; Accepted June 4,2005)
10. Water is wasted by producing unnecessarily NaOH
11. Salt is wasted by producing unnecessarily NaOH
12. It has higher salt consumption than single cells and simple cells
13. It has higher operating cost than simple cells and single cells
14. It needs to purchase the chemical disinfectants continually
15. It uses more current through electrolysis, high current will generate heat through the electrolytic sheets
16. Large amount of investment is required

4. Type of Some Ordinary Diaphragm :

In total, microporous materials with average pore size less than one micron can be used for diaphragm. Although, it is necessary to have sufficient pore size for passing of electricity when pores of diaphragm are filled by electrolyte and also, it should be efficient to prevent the mixing of anolyte and catholyte. In This section, some of the most widely diaphragm that used for producing hypochlorous acid will be reviewed (S, February (2013)):

1. Ceramic diaphragm

The ceramic diaphragm is one of the common membranes for separating anolyte and catholyte in production of the hypochlorous acid. There are two main differences between membrane and diaphragm, type of material and the size of their pores. Membrane pores are smaller than diaphragm pores. The diaphragm is made usually by natural material, but membrane is made by modified material for better selectivity.

2. Piezoelectric diaphragm

According to (Susan Trolier McKinstry (State College, 2008), "The piezoelectric diaphragm includes a central, inactive, electrode-free region and an annular shaped interdigitated electrode adjacent to the outer periphery of the central region. The central region may be inactive, or partially active, such as active in an amount of up to about 10% of the diaphragm

area. The diaphragms are actuated by the interdigitated electrodes. The central region may be free of the metal used to make the interdigitated electrode. Alternatively, the central region may include the metal used to form the annular interdigitated electrode. Preferably, the central region is free of the metal used to make the interdigitated electrode. The piezoelectric diaphragm has an upper surface and a lower surface, and an annular region bordering a central region on the upper surface of the diaphragm. The annular region is in an active state when the central region is in an inactive state, and the annular region is in an inactive state when the central region is in an active state. The active state is present in any one of the annular region or central regions when an interdigitated electrode is present in that region. The interdigitated electrode may include a composite metal layer that includes an adhesion promoting metal layer in contact with the piezoelectric layer and a highly conductive metal layer in contact with the adhesion promoting layer. Alternatively, the interdigitated electrode may include only a highly conductive metal, such as Pt. When any of the annular or central regions are in an inactive state, that region may include the metal used to form the interdigitated electrode. Preferably, when any of the annular or central regions are in an inactive state, that region is free of the metal used to form the interdigitated electrode”.

3. Ion-selective diaphragm

Ion-selective diaphragm is a new technology in electrochemical cells, which is separated anodic and cathodic spaces. “The main distinctive feature of the given process is that ion transfer selectivity in the course of electrolyte aqueous solution electrolysis is achieved thanks to micro-filtration ceramic diaphragm made of zirconium, aluminum and yttrium oxides, which is placed between the electrodes of an electrochemical system, due to creation in the volume of diaphragm porous space of current density and pressure gradients controlling the rate and movement direction of water and charged particles (ions) it contains in the diaphragm pores”. Ion-selective electrolysis diaphragm is a highly and effective technology for separating anolyte and catholyte zone and also, it used in AQUACHLOR equipment (Vitold Bakhir Ins).

4. porous diaphragm

According to (Dennis F. Dong & Arthur L. Clifford, 1990), “A porous diaphragm for an electrochemical cell is disclosed consisting of an assembly which provides a substantially uniform electrolyte flow rate within a defined range of pressure of the electrolyte as a consequence of varying the head of electrolyte to which the diaphragm is exposed. The porous diaphragm of the invention comprises a plurality of layers of a microporous polyolefin film or a composite of support fabric, resistant to deterioration upon exposure to electrolyte, and said microporous polyolefin film. The plural layered diaphragm can be prepared utilizing multiple or variable layers of said polyolefin film or said composite. Variable layered diaphragms have layers which vary in number from the top end to the bottom end of said diaphragm and have a greater number of layers in bottom area of the porous diaphragm which is exposed to higher pressure as the result of a higher head level of the electrolyte. The force exerted on the diaphragm of invention by head levels of about 6 to about 72 inches or more of electrolyte can be controlled by the diaphragm of the invention can be held within the range of about 0.01 to about 0.5 milliliters per minute per square inch of diaphragm. The diaphragm is particularly useful in Electrochemical cells having at least one electrode characterized as porous and self-discharging”.

4.2.3 Membrane-Divided Cells

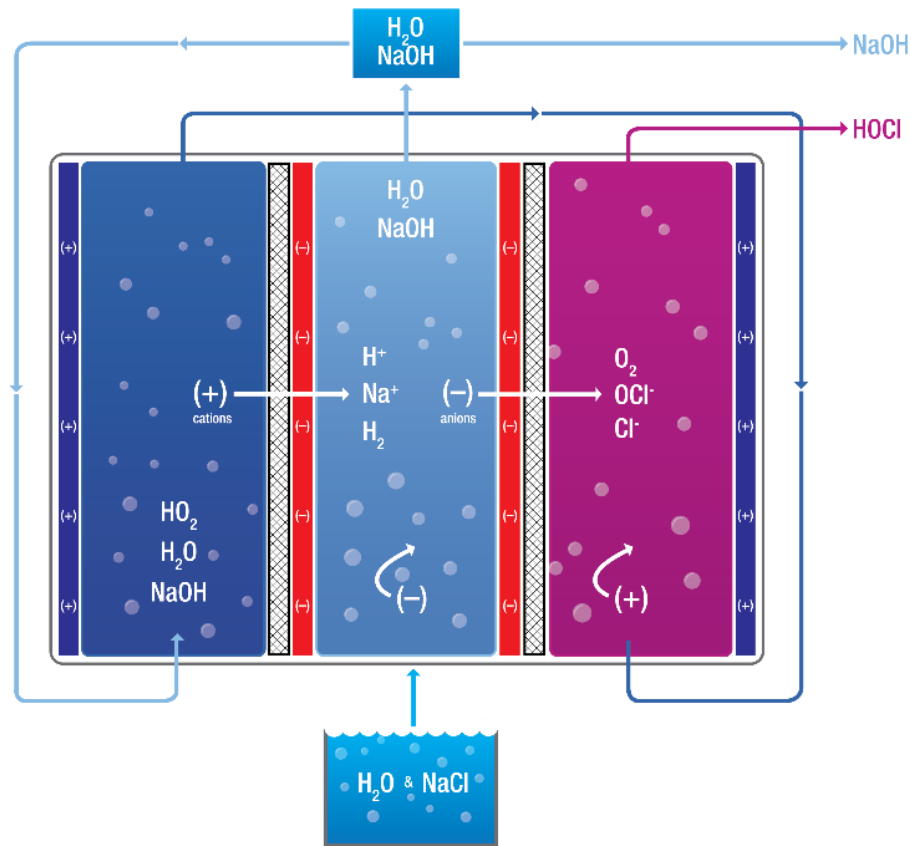


Figure 17 - 4.9 - Schematic of Electrochemical Cell with Membrane

1. Description :

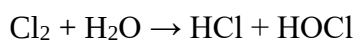
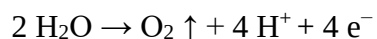
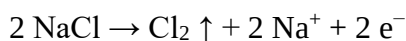
Membrane-divided cells are the third model of electrolytic cells for producing hypochlorous acid. The mechanism of this model is exactly the same as previous model (divided cells by diaphragm) but it compared to previous models have grown very well over the past 20 years. The feed of these devices is water and salt. It mostly operates continuously but also, there are existed batch operating of these models. However, they have some differences with previous model, for instance, the type of divider that is located between the electrodes, the efficiency of device, efficiency and shelf life of hypochlorous acid that produced by these devices. In these devices, a membrane is located between the electrodes that prevents to mixing anolyte and catholyte solutions. The membrane has smaller pores than the diaphragm, so it could better prevent to mixing acidic electrolyzed water and alkaline electrolyzed water fluids. Ultimately, the products from this model has much better quality than the previous model (Site H. a.) and (Technologies, 2015).

In divided cells by membrane, the divider between the electrodes is a membrane. The purpose of membrane exactly is to separate catholyte (cathode zone) from anolyte (anolyte zone) by a fluid. The membrane is a porous material and it exactly the same as the diaphragm, except that fact, it has smaller pores than the diaphragm. Therefore, it is very better to prevent the electrolyte from mixing and also, it has higher efficiency than diaphragm. There are different types of membranes that some of common membrane will be reviewed in section 4. Membranes could be made of different materials, such as

polymers, sulfonated tetrafluoro-ethylene based fluoropolymer-copolymer (Nafion), polypropylene (PP), polyvinylidene fluoride (PVDF), thin, ceramic and metal materials, etc. The shape of the membrane is highly depends on the shape of the cell. If the cell has cylindrical shape, the membrane is cylindrical and if the cell has cube shape, the membrane is a plate. Membrane materials must to have specific properties exactly same as diaphragm, for instance, low electrical resistance because it does not increase energy consumption, low price because it is economical, high physical and chemical stability to have more lifespan, high resistance to prevent mixing of anolyte and catholyte, except ions that must move from the anode to the cathode or vice versa (Clark, 2007 (modified June 2015)), (Group A. , 2020), (Clark, 2007 (modified June 2015)), (Thalles A. Andrade*, 2019), (Group F.), (LAMBERT & VAN SCHAİK, 23 June 2016), (Yu. I. Komolikhov, July, 2020) and (Henry W. Schussler (Harrison City, May 10, 2011).

In summary, the principle of generating anolyte and catholyte in divided cells by membrane exactly same as divided cells by diaphragm, the reactions as follows (Tian Ding, 2019):

Equation 3 - 4.3 - Reactions in Anolyte



Equation 4 - 4.4 - Reaction in Catholyte

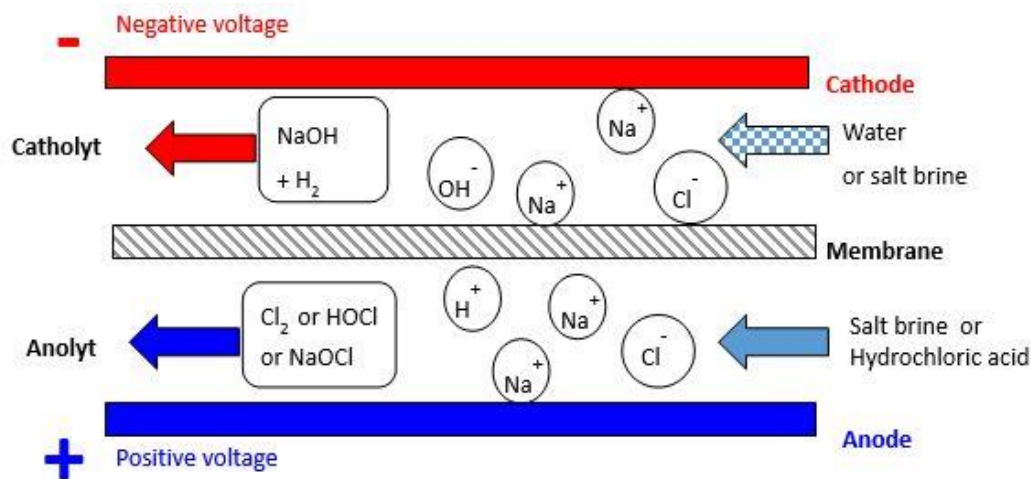
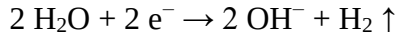
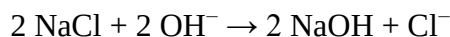


Figure 18 - 4.10 - Scheme of Electrolytic Cell with Membrane

The membrane-divided cell generally comprises an anolyte compartment containing an anode, a catholyte compartment containing a cathode. The divider between electrodes could increase the performance of these devices and quality of the hypochlorous acid. Also, it increases stability of HOCl. The pH levels of catholyte and anolyte is different because different reactions performed in each fluid and there are different ions and compound in each fluid. The main reaction that occurred in catholyte is: $2 \text{H}_2\text{O} + 2 \text{Na}^+ \rightarrow 2 \text{NaOH} + \text{H}_2$ and the main reactions that occurred in anolyte is:

$\text{H}_2\text{O} + \text{Cl}_2 \rightleftharpoons \text{HOCl} + \text{H}^+ + \text{Cl}^-$. In anolyte, anions (chloride and hydroxide) move to the anode and become hypochlorous acid, singlet oxygen, peroxide anion, superoxide, ozone, monoatomic, oxygen and free radicals, hydrochloric acid, chlorine gas, known to possess antimicrobial properties. In catholyte, cations (hydrogen and sodium) move to the cathode and become hydrogen gas (H_2) and sodium hydroxide (NaOH). For example, according to figure 4.11, this is a schematic of membrane-divided cell from Danish Clean Water Company. In this scheme, the composition of anolyte solution and catholyte solution and pH level of each are mentioned (Samuel C. Perry, 2020), (Group A. , 2020), (Site H. a.), (Ins, 27-Jun-2008), (Group A.), (TIM QUINN, March 2012) and (Technologies, 2015). Example for properties of products of divided cell by membrane. According to (Site K.), “The solution dissociates into an acidic solution from the anode (anolyte), with a pH of 2 to 3, an oxidation-reduction potential (ORP) of >1100 [mV], and an active chlorine content (ACC) of 10 to 90 [ppm], and a basic solution from the cathode (catholyte), with a pH of 10 to 13 and an ORP of -800 to -900 [mV]”.

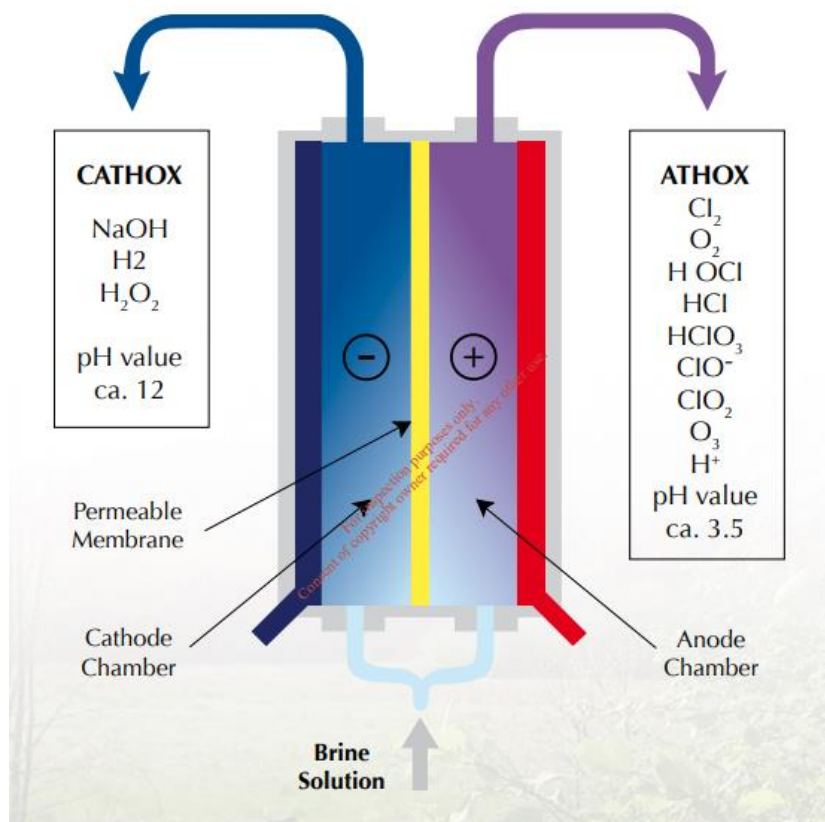


Figure 19 - 4.11 - Electrochemical Cell with Membrane

According to (Georgi Gluhchev, 2015), “The parameters of pH, the redox potential, ORP and the electrical conductivity of the anolyte/catholyte depend on different factors including the ratio of water volumes in the two electric chambers, the material of electrodes, NaCl salt concentration, the temperature, electric voltage and processing time”. As is known from previous chapters, hypochlorous acid is present in a wide range of pH levels and its stability is highly dependent on pH level and Free available chlorine concentration. These devices are controlled by pH and FAC controllers because product must have specific properties for increasing its stability and shelf life, the

produced hypochlorous acid has shelf life some weeks and depends on storage and packing conditions. This model of these devices is an industrial model for producing hypochlorous acid and it operates continuously. In continuous process, to increase the efficiency of these device, two or more electrodes can be used as anode and two or more electrodes can be used as the cathode. Also, this model of electrolytic cells needs less labors and operators because the solution stored in the storage tank continuously. Membrane-divided cells are very efficient and better than diaphragm-divided cells and simple cells for producing hypochlorous acid industrially. Many companies produce this model and the most famous of them are FumaTech, Aquaiox, Geemblue, Unido, NaOClean, BAKHIR & ECT, SionTech, Envirolite, ProMinent, Chlorking, Tianno, Safewater, NaOClean and Dinol (Robert Guillaume, Jean-Pierre Pleska, & Jean Indeherbergh, 1981) and (Muhammad Imran AL-HAQ, Received April 6,2005 ; Accepted June 4,2005).

In divided cells by membrane, to increase the efficiency of the device and improve the quality of the hypochlorous acid, different controllers are used, such as PLC. According to (Samuel C. Perry, 2020), “The strength of the Brine (Salinity) is carefully controlled by the PLC to ensure optimum production of the disinfection agents and to minimize any salt residue in the finished product. By carefully controlling the flow, the salinity and the power our generators can ensure a consistent product in terms of both pH value and free chlorine. The PLC unit monitors the variable parameters within the system up to 300 times per minute and makes the necessary adjustments to ensure consistency of product”. To increase shelf life and effectiveness of hypochlorous acid, several important parameters in electrolytic cells must be monitored and controlled, these important parameters are as follows (Ins, 27-Jun-2008) and (INC):

- pH of anolyte and catholyte
- Conductivity of anolyte and catholyte
- ORP of both anolyte and catholyte
- Free available chlorine concentration of hypochlorous acid solution (anolyte)
- Concentration of sodium hydroxide solution (catholyte)
- Time of contacting between feed and electrodes (residence time)
- Amount of salt consumption

These parameters could be change by changing the operating conditions of the electrolytic cells, for example, if the properties of the output products are not favorable. To solve these problems, some devices returned the anolyte and catholyte outputs to the cell by using a bypass line for increasing residence time, or changes the amount of inlet brine, or changes the inlet pressure by increasing the speed of pump, or changes the current and voltage of electrolytic cell (Site K.).

These cells need to be installed because the water must enter the cell at the higher pressure than the usual tap water piping pressure to facilitate the moving of ions through the membrane. Also, water must to be filtered before entering the divided cell by diaphragm to remove hardness from water and increasing the divider efficiency between the electrodes because these hardness in water may get stuck in the divider pores and clogs it. If the purified water used, the cell does not need to be repaired and cleaned for longer time. In Chapters 5 and 6, maintaining and cleaning cells and water purification, etc. are thoroughly reviewed. Also, if these hardness does not separate from water, the presence of these hardness, such as calcium, magnesium around the cathode will cause formation of fouling on the cathode and divider. It reduces the efficiency of the device (Chambron, Received: 26 September

2013; in revised form: 3 December 2013 / Accepted: 4 November 2013 / Published: 16 December 2013).

On-Site generators of this model are very common and useful because the hypochlorous acid has a limited shelf life. Shelf life of it depends on its pH level and free available chlorine concentration. In some devices, if operating conditions are not controlled, the hypochlorous acid solution may have a shorter shelf life. So, on-site hypochlorous acid generators are economic option for producing HOCl. Many hospitals in Russia and Commonwealth of Independent States (CIS) use anolyte in their sterilization procedures. Also, in many medical centers, hospitals and public centers in Russia and Japan, produces HOCl on-site. They commonly used membrane-divided cells for producing HOCl because in addition to hypochlorous acid, sodium hydroxide is also produced as by-product. Sodium hydroxide is an excellent antiseptic for ceramic surfaces and hospital floors hygienic purposes in the hospital and it is also used to produce many chemical substances in many industry fields.

According to figures 4.12 and 4.13, the water must be purified before entering the cell and hardness removed from water, then the required proportion of concentrated brine solution mixed with the purified water. Some cells need a pump to increase pressure, such as divided cell by membrane or divided cells by diaphragm. In the most common divided cells, there is a pump to increase the pressure of feed. The solution of water and salt enters in both chamber (i.e. anolyte chamber and catholyte chamber). According to (Daniel P. Longhenry (Bloomington, 2014), "The salt concentration of a first salt solution entering the cathode chamber is substantially less than the salt concentration of a second salt solution entering the anode chamber. This increases the production of hypochlorous acid in a resulting anolyte stream, providing an effective disinfectant". In electrolytic cell, the ions move between the anode and the cathode, redox reactions occur and hypochlorous acid solution and sodium hydroxide solution produced. Finally, the output of each chamber stored into the storage tank. (Daniel L. Joynt, 2015).

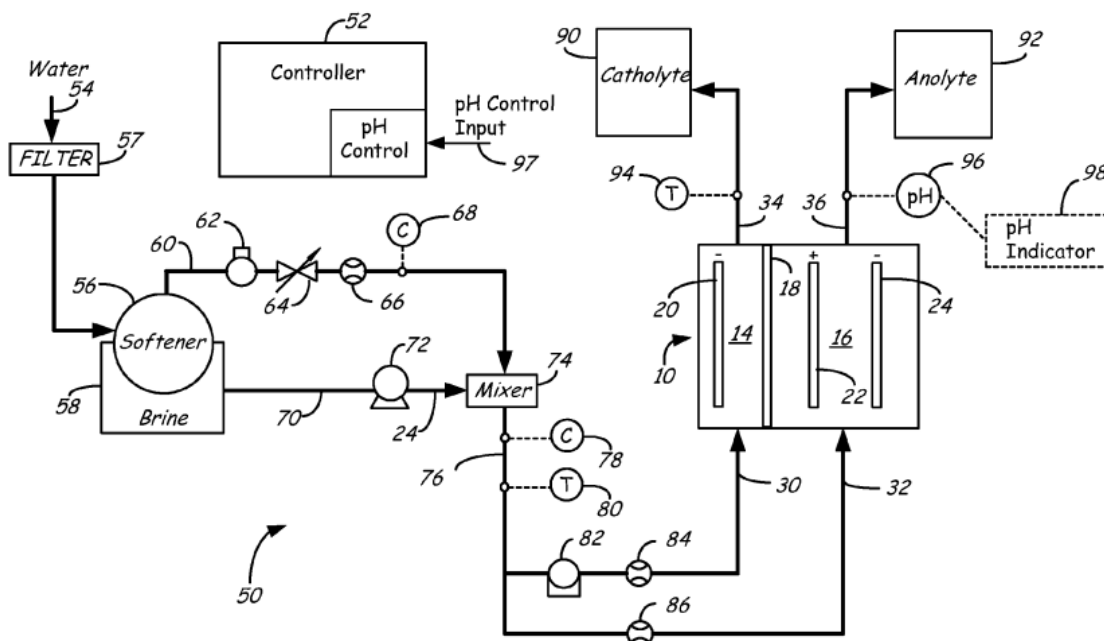


Figure 20 - 4.12 - PFD of Electrochemical cell with Membrane Plant

Hamed Haddadzadeh
2020 - 2021

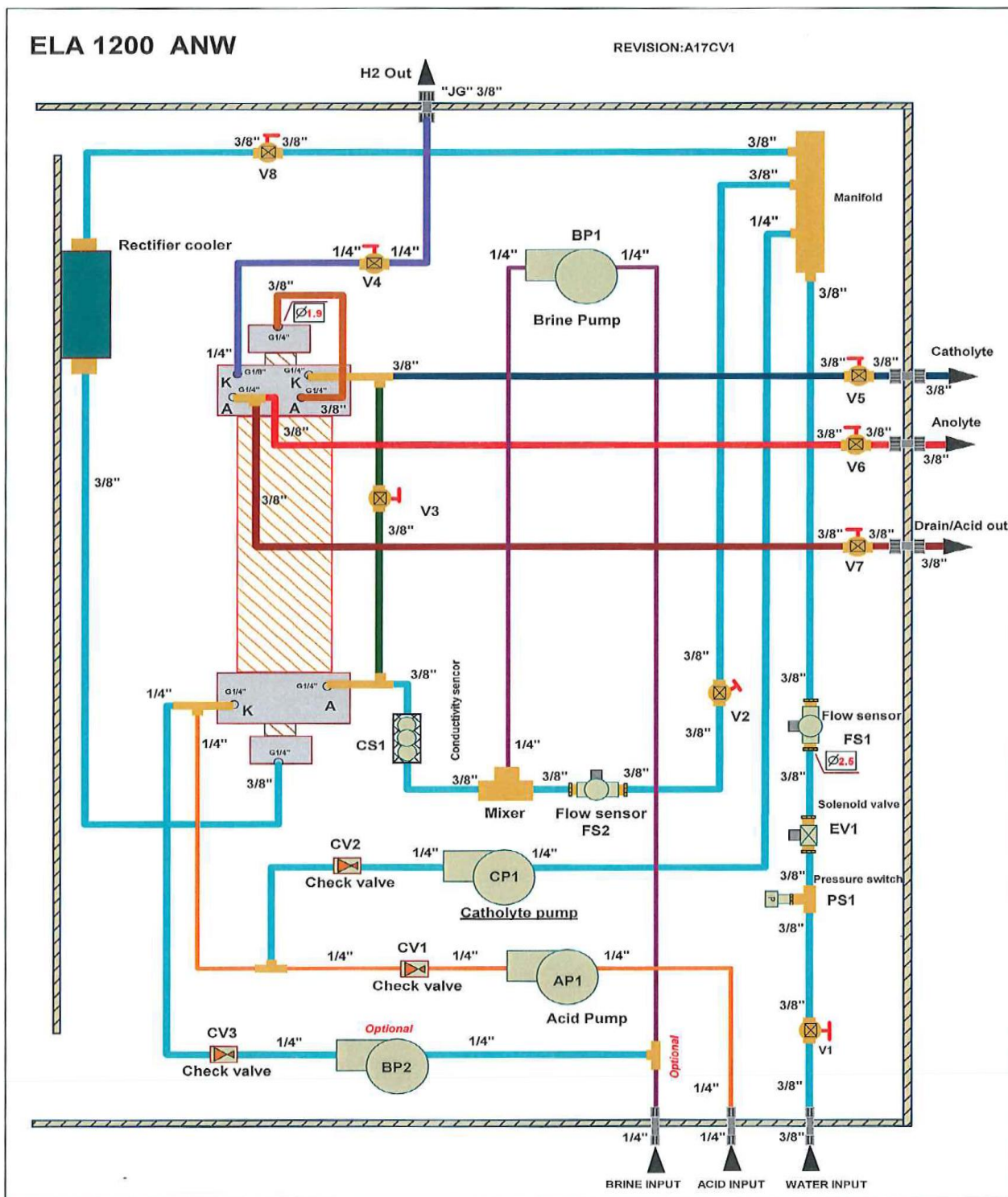


Figure 21 - 4.13 - Schematic of HOCl Generator On-site Plant, Electrochemical cell with Membrane

(Corporation E.).

According to figure 4.14, in the Chlorking company, “Most electrolyzed water systems use a membrane separating the cathode from the anode, which produces anolyte (HOCl) and catholyte (Sodium hydroxide). This technology is very unreliable and requires frequent maintenance. This technology also requires the sodium hydroxide run to waste as it is a by-product of HOCl production”. However, Sodium hydroxide is a very useful and strong antiseptic solution (David-Lee Van Niekerk, 2011) and (Company C.).



Figure 22 - 4.14 - The Chlorking HYPOGEN Device

2. Advantage of Membrane-Divided Cell :

1. One of the most important advantages of the membrane-divided cell is that the overall plant process requires less energy than either the diaphragm cell (Corporation B. &., 2010 by John Wiley & Sons)
2. It takes up space like a small cabinet
3. It has higher efficiency than simple cells and diaphragm-divided cell because pore size of membrane is very small
4. Long Service life because water and salt must be treated and also most of these devices use titanium electrode coated by platinum and iridium for protection from oxidation, largely increases the service life of electrolytic cell
5. This device has fully Automatic Operation; Most of those devices use PLC; On-line display PH level, ORP, conductivity, electrolytic current and running time, etc (Group G.)
6. It produces two byproducts, anolyte contains hypochlorous acid (HOCl) and catholyte contains Sodium hydroxide (NaOH)
7. It could produce hypochlorous acid with a wide range of free chlorine available concentration
8. It has a wide range of pH, pH range of it is controlled in the 2 to 13.
9. Hypochlorous from these devices has longer shelf life than HOCl from diaphragm-divided cells and simple cells (Muhammad Imran AL-HAQ, Received April 6,2005 ; Accepted June 4,2005) (Company I.)
10. High production capacity
11. Continuous operating

12. It can be operating on-site plant
13. Feed of these devices is pure water with NaCl salt; it therefore has less adverse impact on the environment
14. It is environment-friendly device
15. After the initial cost of the electrolysis device, operational expenses are minimal. Thus, the use of generated hypochlorous acid is quite cost-effective
16. It has higher efficiency than diaphragm-divided cells and simple cells
17. Less corrosion occurs in these devices
18. In addition to the main electrochemical reaction that occurs with the electrodes, the high intensity of the electric field on the surface of the electrode gives the water and its dissolved salts some electro-metastability, which increases its ORP by the order of - 800 [mV] and + 1200 [mV] respectively in the catholyte and anolyte.
19. In industrial field, it could be more efficient than simple cells and also, labors and operators is needed in divided cells by membrane

3. Disadvantages of Membrane-Divided Cell :

1. Membrane-divided cells are relatively more expensive than simple cells and diaphragm-divided cells
2. It has high maintenance cost
3. It has installation cost
4. Power consumption of membrane-divided cells is larger than simple cells and divided cells by diaphragm (WATANABE, TAKAMATSU, MIYAHARA, ANDO, & NISHI, 30.06.1995)
5. It uses more current through electrolysis, high current will generate heat through the electrolytic sheets
6. In some machines, if the pH is set lower than 5, chlorine gas is produced in addition to other species of free chlorine available (e.g. HOCl and OCl⁻ ions). In such cases, the operator must protect himself from chlorine fumes. Otherwise, these devices are safe for the environment as well as for the operator.
7. Water loss is significant by producing unnecessarily NaOH
8. Salt loss is significant by producing unnecessarily NaOH
9. The initial purchase of the device, pump, pipe and fittings may be costly (Muhammad Imran AL-HAQ, Received April 6,2005 ; Accepted June 4,2005)
10. It used of treatment salt
11. It used of treatment water
12. It has higher salt consumption than single cells and simple cells
13. It is heavier than single cells and simple cells
14. It needs to purchase the chemical disinfectants continually
15. It has higher operating cost than simple cells and single cells
16. Large amount of investment is required

4. Type of Some Ordinary Membrane :

In general, microporous materials with smaller pores than diaphragm used for membrane. Membrane may be natural materials or modified material. Although, it is necessary to have sufficient pore size for passaging of electricity when pores of membrane are filled by electrolyte and also, it should be efficient to prevent the mixing of anolyte and catholyte. In This section, some of the most widely membrane that used for producing hypochlorous acid will be reviewed (S, February (2013)):

1. Electro-Membrane

Electro-membrane is a technology for separating anolyte and catholyte in electrolytic cells by apply electric potential gradient as driving force of ion transport. It has five main processes for separating electrolyte solution:

1. Electrodeionization (EDI), 2. Electrodialysis (ED), 3. Electrodialysis reversal (EDR), 4. Electrodialysis with bipolar membrane (EDBM), 5. Capacitive deionization (CDI) (Site L. T.). According to (Site L. T.), “Advantages of electro-membrane processes: 1.high efficiency of separation of substances without phase transitions, 2.easy continualization and automation, low demands for space, 3.lower energy consumption, compared to traditional procedures, 4.possibility to create closed waste-free technological junctions or entire technologies.

Disadvantages of membrane processes: 1.removal of so-called membrane poisons by pre-treatment of solutions, 2.fouling (creation of coating of poorly soluble substances on the membrane surface)”.

2. Ion-exchange Membrane

Ion-exchange membrane is one of basic elements of electro-membrane technology. Ion-exchange membrane mostly made from polymer. There are two ion-exchange membrane for separating process (Tanaka, January 2015) (Strathmann, 2004):

1. Cation-exchange membranes (CM): According to (Site L. T.) and (Tomohiro YAMAGUCHI, 2020), “These membranes contain in their polymeric matrix acid ion-exchange groups that have negative electric charge ($-\text{SO}_3^-$, COO^-), allowing for free passage only of those particles with positive charge. Negatively charged particle passage is drastically reduced”. So, cation-exchange membrane only allows cations (positive ions) to pass through membrane. In hypochlorous acid production process, it means only sodium ions, hydrogen ions and other positive ions can pass through membrane.

2. Anion-exchange membranes (AM): According to (Site L. T.), “These membranes contain in their polymeric matrix basic cation-exchange fixed groups ($-\text{NR}_3^+$, where R is hydrogen or alkyl group), allowing for free passage only of particles with negative charge. Positively charged particle passage is drastically reduced”. So, anion-exchange membrane only allows anions (negative ions) to pass through membrane. In hypochlorous acid production process, it means only OCl^- , OH^- and other negative ions can pass through membrane.

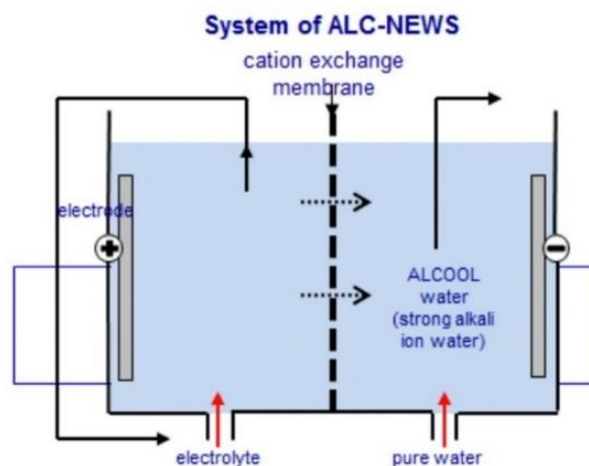


Figure 23 - 4.15 - Scheme of Cell with Cation-exchange Membrane

3. Bipolar Membrane

Bipolar membrane is one of basic elements of electro-membrane technology. It has two layers for separating process, generally consists of an anion-exchange layer and a cation-exchange layer. One of problem of bipolar membrane is typically unstable in high current cells (Krzysztof MITKO, 2015) and (Wilhelm, 2001). According to (Site F. C.), "Applying bipolar membrane with DC current, water is split inside the membrane and then proton (H^+) and hydroxyl ion (OH^-) are generated. This unique function of water splitting is utilized for production of an acid and a base from a corresponding salt in combination with conventional monopolar ion exchange membrane. In its simplest form a bipolar membrane is a cation-exchange membrane laminated together with an anion-exchange membrane, through an intermediate layer (the "junction" layer). The intermediate layer is the most important part of the membrane. The principle of "splitting" water by using a bipolar membrane, water diffuses from across the cation- and anion-exchange layer to junction layer where it dissociates into H^+ and OH^- ions. The H^+ ions then migrates across the cation-exchange layer towards the negative electrode while the OH^- ions migrate across the anion-exchange layer to the positive electrode".

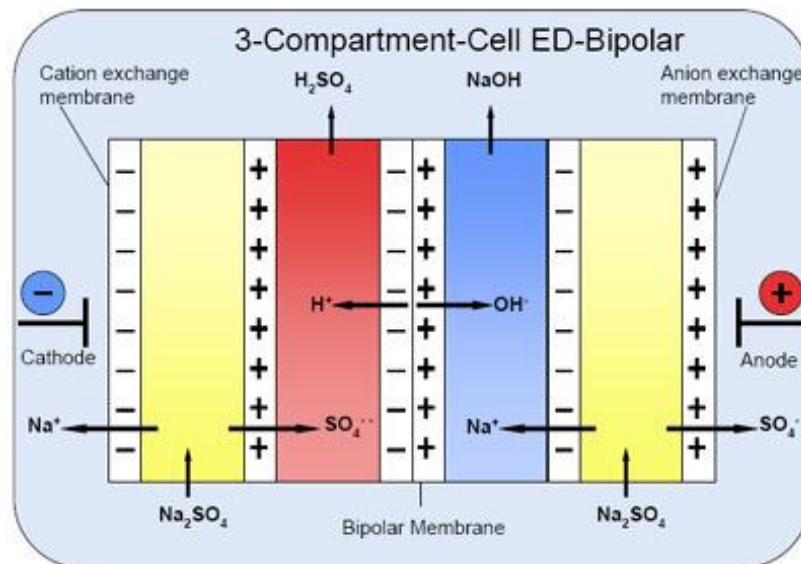


Figure 24 - 4.16 - Scheme of Bipolar Membrane

Example for producing hypochlorous acid solution and sodium hydroxide solution by passing salt solution across a bipolar membrane, final parameters of anolyte in this process: an acidic solution with pH is approximately 2.6, ORP is 1150 [mV] and a chlorine concentration 40 and 90 [ppm]. Final parameter of catholyte in this process: a basic solution with pH is approximately 11.4 and ORP is 795 [mV] (Subrota Hati, 2012).

4. Dual Membrane

Dual membrane consists two layers of membrane, a cation-exchange membrane and an anion-exchange membrane. It has three chambers for electrolyte solution. functional electrolyzed water of pH 2.7 ~ 12 excluding salt ($NaCl$) which is used as an electrolyte through the middle chamber which can divide salt ($NaCl$), electrolyte, into Na^+ ion and Cl^- ion completely.

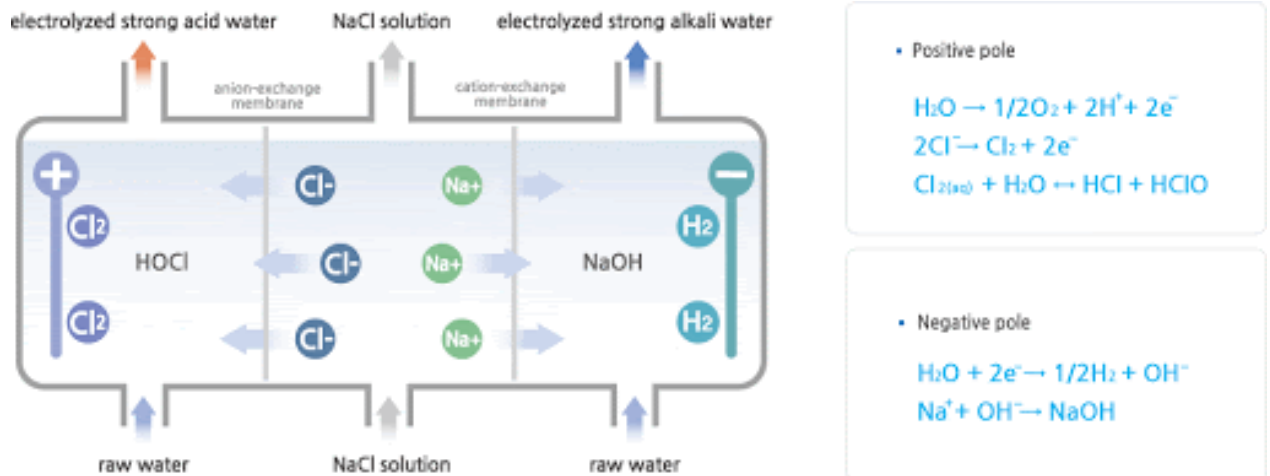


Figure 25 - 4.17 - Scheme of Dual Membrane Configuration

5. Dialyzer Membranes

According to (Filimonova, Received March 21, 2020; revised April 3, 2020; accepted April 10, 2020), “Diffusion dialysis, as a means of membrane separation, is a practical method for treating solutions of spent acids or bases containing salt ions. It is based on the difference in concentrations on different sides of the cation or anion exchange membrane and its operation does not require electric energy”. The common electro-membrane process is electrodialysis. Figure 4.18 is a schematic view of the electro-dialyzer membrane.

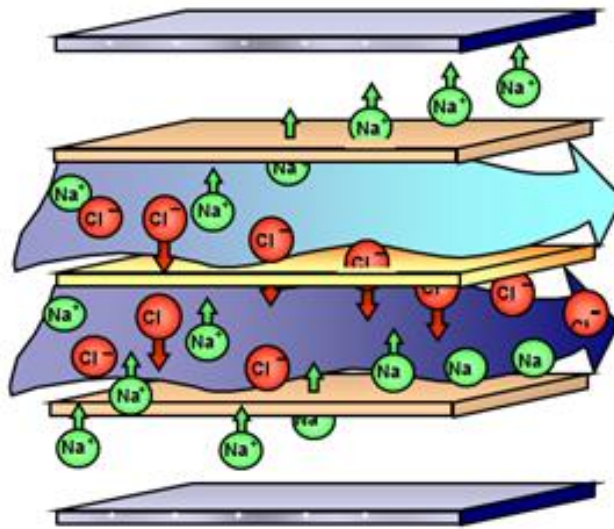


Figure 26 - 4.18 - Scheme of Dialyzer Membranes

6. Ceramic Membrane

The ceramic membrane is one of the common membranes for separating anolyte and catholyte in production of the hypochlorous acid. According to (Dionisio da Silva Birona, 2016), “Many ceramic materials have been used in the manufacture of membranes, among which stand out alumina, silicon oxide, zirconia, titania, mullite and cordierite”. Ceramic membrane is a porous fine ceramic and it has been used in many hypochlorous acid generators devices because its reasonable price, long lifespan, excellent resistance to acid, optimal pore size, high

permeability and simple separation mechanism (Site G. T.), (Monsanto, 1997) and (Bakhrir V.M. D. o.).

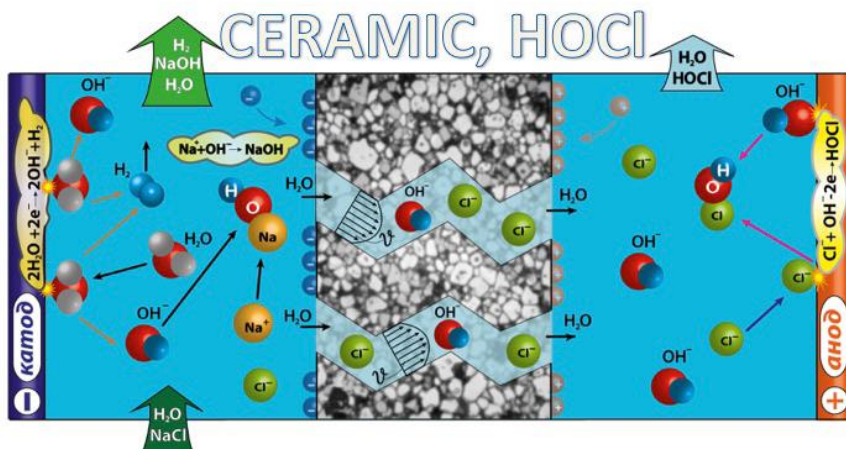


Figure 27 - 4.19 - Ceramic Diaphragm with Pore Sizes from 0.01 to 0.1 Micron Transforms into An Ion-selective Membrane (Not Only Cationic, But Also Anion-active) Under Exposure of The Superposition of The Pressure Field and The Electric Field

7. Horizontal Membrane

According to (K Umimoto, 2013) and figure 4.20, “A vertical-type electrolytic tank with an asymmetric structure having a horizontal membrane, an anode chamber (large chamber) located below the membrane and provided with an anode electrode plate at a position an appropriate distance away from the membrane, and a cathode part (small chamber) disposed above the membrane and provided with a mesh-type cathode electrode plate at a position near the membrane”.

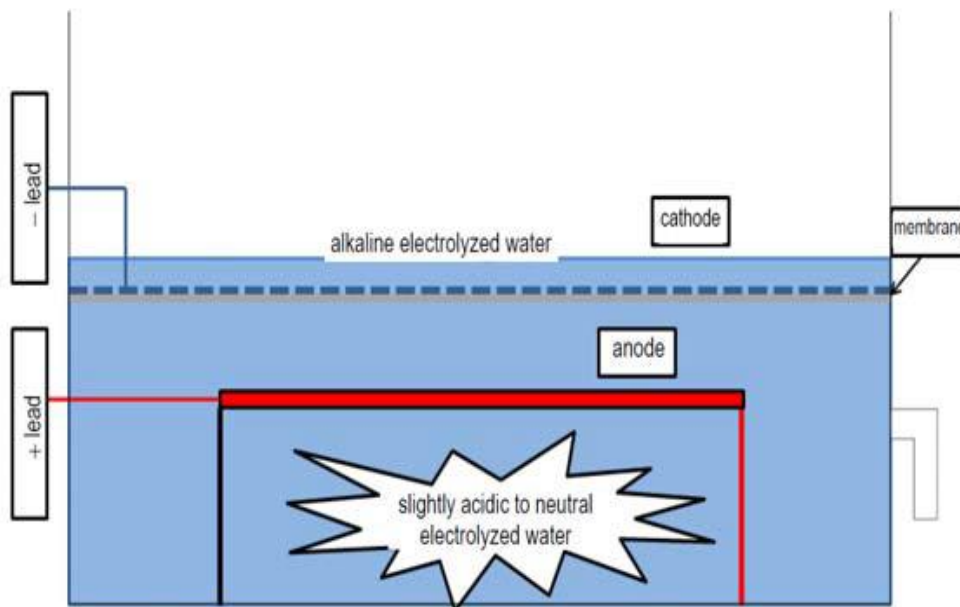


Figure 28 - 4.20 - Scheme of Horizontal Membrane

4.2.4 Modified Undivided Cells - Single Cells

According to figure 4.21, this is a schematic of the single cell which is latest technology for producing hypochlorous acid, pH controlled by emulsification electrolyte elements via high speed inducer wheel for better mixing.

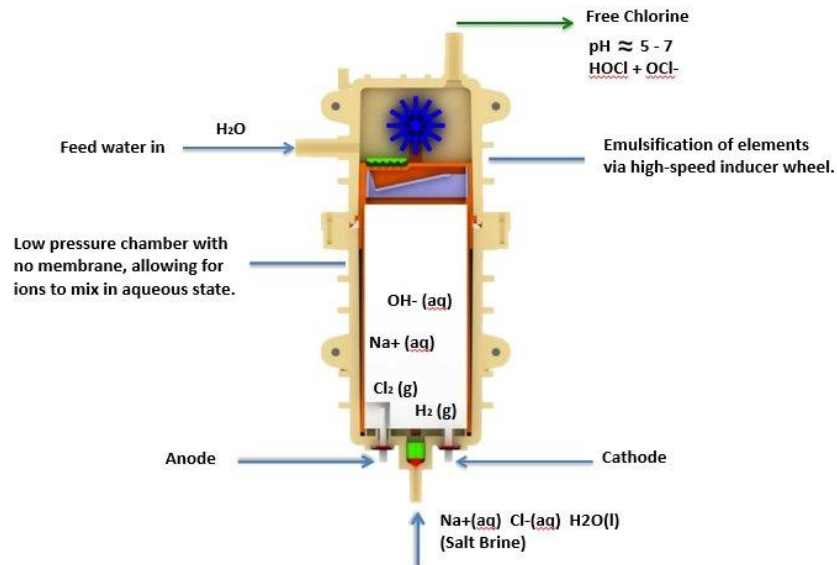
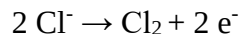
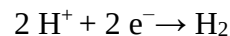
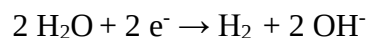


Figure 29 - 4.21 - Scheme of New Generation of Single Cell

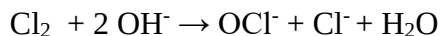
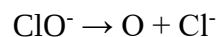
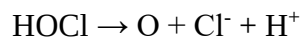
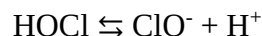
Equation 5 - 4.5 - Anode Reaction



Equation 6 - 4.6 - Cathode Reaction



Equation 7 - 4.7 - Free Chlorine Generation



1. Description :

Single cells are the fourth model of electrolytic cells for producing the hypochlorous acid. Single cells are designed simpler than divided cells because the absence of divider and also, avoids the cost of the membrane or diaphragm and gaskets and fitting required to fit the membrane or diaphragm. These devices are the latest technology to produce the hypochlorous acid. This model has some differences from previous models, such as divided cells and simple cells. In these devices compared to the divided cells, there is no divider between the electrodes. So, these devices have a body of cell, a DC current

power supply, an electrolyte solution and two or more electrodes for the anode and cathode in electrolysis system. The difference between single cells and simple cells is about the presence of controllers, size of device and mode of electrolysis process (i.e. batch or continuous) because these devices mostly operates continuously. The feed of these devices is acidified brine, it acidified by Hydrochloric acid (HCl) and another feed is water and hydrochloric acid. Due to the absence of membranes or diaphragms in these cells, salt and water consumption is lower than previous models because sodium hydroxide is no longer produced as a by-product of this reaction and the product of these devices is only hypochlorous acid solution with a low pH levels of between 4.5 to 6.5 ORP is >800 [mV]. This hypochlorous acid solution has more stability because the product does not have to be present at two different pH levels and ORP level like anolyte and catholyte in divided cells. However, the feed has acidic pH level, so the product of this reaction is mostly slightly acidic electrolyzed water (SAEW) or natural electrolyzed water (NEW). Definition of SAEW and NEW are known from description of divided cell by diaphragm (Hyun-Ji Kim, 2019), (Dr.Sohrabi, 2020), (Site H. a.), (Angelica Naka, 2020 Feb 18), (Tian Ding, 2019), (Samuel C. Perry, 2020) and (WATANABE, TAKAMATSU, MIYAHARA, ANDO, & NISHI, 30.06.1995).

In these devices, the pressure of acidified brine (feed of the device) is the usual water piping pressure and there is no pump is needed for increasing the pressure of feed. Therefore, it is easier and cheaper to maintain the device for a long time. however, in some model of single cell, the pump is used to controll the flow of feed. For example, according to figure 4.22 : (A) Water tank, (B) Electrolytic cell, (C) Power supply, (D) Master flex, (E) Electrolyte , (F) SAEW produced. Process description : Tap water flows into the water tank, (A) and undergoes water electrolysis in the electrolytic cell, (B). Amperage and voltage have been arranged through switch mode power supply, (C) and electrolyte, (E) is controlled by master flex, (D) that drives flow rate of electrolyte. Finally, SAEW, (F) is generated through the EW generator system (Ali Turab Jafry, Received February 13, 2017; Revised May 4, 2017; Accepted May 23, 2017).

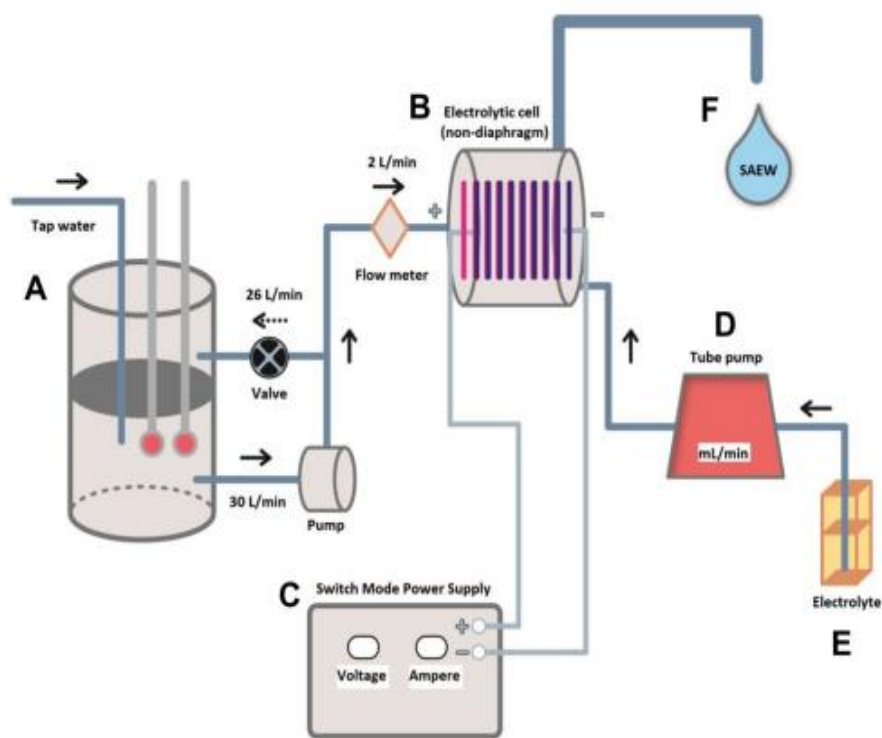


Figure 30 - 4.22 - Schematic Diagram of The Electrolyzed Water Generator System Implemented for The Production of SAEW in The Study

Hamed Haddadzadeh
2020 - 2021

Also, water does not need to be purified and ordinary tap water can be used. However, if purified water is used as feed, cell maintaining is easier and the formation of fouling on the cathode does not occur. In addition to all the advantages, there are also disadvantages. One of the main and common problems in this model is the bubbles formation in the cell (hydrogen gas is produced as bubbles) and it reduces the efficiency of the cell because it reduces the available surface area for electrolysis. The Combination of high current and temperature causes the bubble generation in the electrolytic cell (Ali Turab Jafry, Received February 13, 2017; Revised May 4, 2017; Accepted May 23, 2017) and (Andrew K. Boal, Spring 2009, Vol. 9, Issue 1).

As is known, the output product (hypochlorous acid solution) of each of these last three models can be produced in a wide range of pH level, free available chlorine concentration, ORP and stability. It is necessary to monitor the properties of the hypochlorous acid solution and it must be controlled in specific range of properties. According to (Angelica Naka, 2020 Feb 18), "An anolyte in the pH range of 5 to 7. This pH range is optimal for hypochlorous acid in regards to stability and effectiveness as a sanitizer. SAEW is produced by electrolyzing an aqueous solution of NaCl or HCl using a non-membrane electrolytic cell". Shelf life of hypochlorous acid, available free chlorine concentration, pH level, ORP level and effectiveness of hypochlorous acid against different viruses depends on the residence time of feed in electrolytic cell, water flow rate, temperature, salt consumption, current and voltage, storage and packing conditions, materials of electrodes and cells. By changing these parameters, the hypochlorous acid solution with the desired quality will be produced (Ali Turab Jafry, Received February 13, 2017; Revised May 4, 2017; Accepted May 23, 2017) and (Engineers).

This model of hypochlorous acid generators is an industrial model and mostly operates continuously. the continuous process of single cells is mostly used in industrial levels because it is much more economical and less operators and labors are needed. On-Site generators of this model are very common and useful because as is known, the hypochlorous acid has a limited shelf life, Shelf life of it depends on its pH and free available chlorine concentration. In some devices, if operating conditions are not controlled, the hypochlorous acid solution may have a shorter shelf life. So, on-site hypochlorous acid generators are economic option for producing HOCl. Many hospitals in Russia and Commonwealth of Independent States (CIS) use anolyte in their sterilization procedures. Also, in many medical centers, hospitals and public centers, produces HOCl on-site in Russia and Japan. Many companies produce this model and the most famous of them are Ecolox Tech, Chlorking, Environize (Angelica Naka, 2020 Feb 18).

According to (Group G.) and figure 4.23, "The strong acid electrolyzed water equipment adopts Japanese electrolysis generating device, which is mainly composed of electrolysis activation tank, platinized titanium alloy electrode plate, power supply and control system. The control system can adjust voltage, current, and electrode polarity. The electrolyzed water equipment adopts titanium-coated platinum-iridium electrode material to prevent oxidation of the electrode plate during electrolysis and improve the life of the electrode and the whole equipment. In the process of water production, the electrolyzed water equipment can produce weak alkaline disinfection water with different pH values (2~4) by adjusting the current to meet the needs of different customers. Adopt the most advanced electrolysis water manufacturing process: electric separation and combination technology to ensure the treatment of water quality. The system is fully prepared and has ample margin, fully automatic operation, and the pH of the effluent is stable. The strong acid electrolyzed

water equipment has low operating cost and can produce micro-acidic electrolyzed water in a continuous operation”.

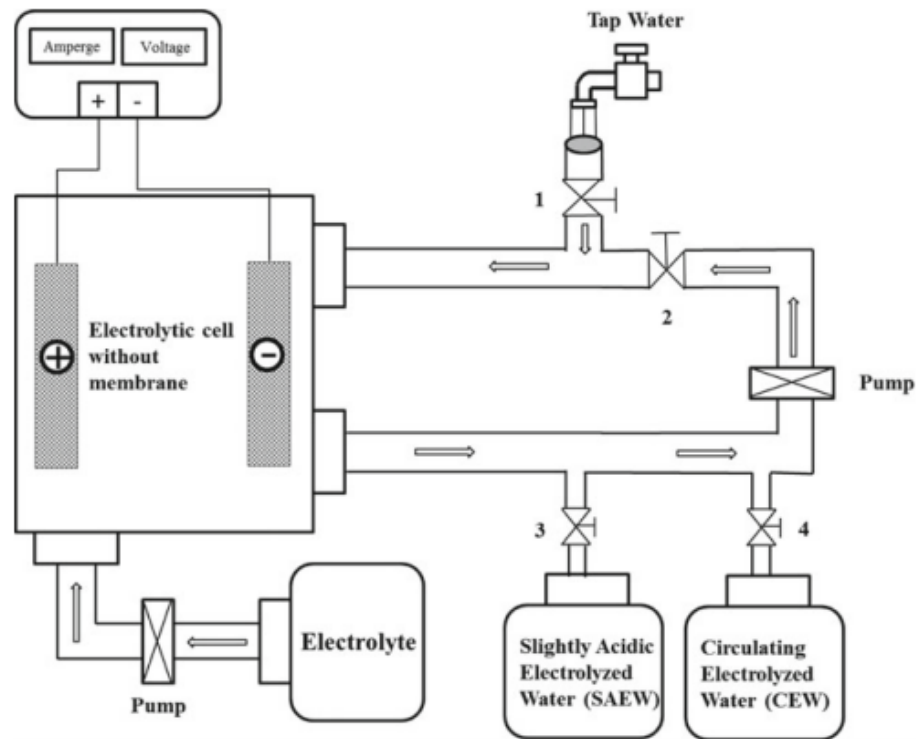


Figure 31 - 4.23 - Schematic of Generation of SAEW and CEW by Using An Electrolysis Chamber Without The Separating Membrane

Hint: In figure 4.23, when switches 1 and 3 are opened and 2 and 4 are closed, SAEW can be generated; Otherwise, CEW can be produced.

2. Advantages of Single Cell :

1. Less power consumption than divided cells
2. Continuous operating, produces hypochlorous acid continuously
3. It can be operating on-site
4. Low production cost (Site N.)
5. It has lower price than the membrane-divided cells
6. Feed of this device is water, NaCl salt or HCl; it therefore has less adverse impact on the environment
7. It is environment-friendly device
8. It has acidic pH, pH range of it is controlled in the 4 to 7.
9. Having fewer potential health hazards due to its pH range.
10. In addition to the main electrochemical reaction that occurs with the electrodes, the high intensity of the electric field on the surface of the electrode gives the water and its dissolved salts some electro-metastability, which increases its ORP is $> + 800$ [mV]
11. It is available in packs or portable machines and take up a little space, smaller place than divided cells

12. Shelf life of hypochlorous acid from this model is longer than hypochlorous acid from divided cells and also simple cells
13. High production capacity
14. Higher efficiency than divided cells
15. It could produce hypochlorous acid with a wide range of free chlorine available concentration
16. Low water and salt consumption
17. Fully Automatic control; PLC mostly used
18. In industrial field, it could be more efficient than divided cells and simple cells
19. After the initial cost of the electrolysis device, operational expenses are minimal. Thus, the use of generated hypochlorous acid is quite cost-effective
20. It uses less current through electrolysis

3. Disadvantages of Single Cell :

1. Bubbles formation in high current and high temperature
2. It is expensive device
3. It has instillation cost
4. Large amount of investment is required
5. It needs to purchase the chemical disinfectants continually
6. This cell has one product, only produces hypochlorous acid
7. The initial purchase of the apparatus, pipe and fittings may be costly (Muhammad Imran AL-HAQ, Received April 6,2005 ; Accepted June 4,2005)
8. Large maintenance cost
9. In some machines, if the pH is set lower than 5, chlorine gas is produced in addition to other species of free chlorine available (e.g. HOCl and OCl⁻ ions). In such cases, the operator must protect himself from chlorine fumes. Otherwise, these devices are safe for the environment as well as for the operator.
10. In addition to water and NaCl salt, it used Hydrochloric acid (HCl) as feed

Chapter Five

Quality Criteria for Feed Materials

CHAPTER 5 - QUALITY CRITERIA FOR FEED MATERIALS

5.1 Quality and Temperature of Water

5.1.1 Water Temperature

Water quality is a very important parameter as the main component of the feed of electrolytic cell. Inlet water temperature has greatly affecting on the pH level of the output product and the lifespan and maintenance of the electrolytic cell. The allowable temperature of the water entering the cell varies according to the material of cells and its parts (electrodes, sensors and divider, etc). the allowable temperature range is mentioned in the technical specification guideline of each device. In general, the most appropriate inlet water temperature is in the range of 4.5 to 26.5 [°C] (40 to 80 [°F]). If the water entering temperature of the cell is out of this range, it will damage the cell parts and causes financial loss. So, if the water temperature of cell is out of this range, water must be cooled or heated to regulate the temperature of the water entering the system within the specified range. Also, temperatures above 40 [°C] (104 [°F]) might have a negative effect on the antimicrobial effect of hypochlorous acid and its inactivation due to the partial loss of free available chlorine during the heating period (Tian Ding, 2019) and (Andrew K. Boal, Spring 2009, Vol. 9, Issue 1).

5.1.2 Water Hardness and Water Softening and Purification Technologies

Water composition is also very important parameter as the main component of the feed of electrolytic cell. According to (Tian Ding, 2019), “The authors also evaluated the effect of water hardness on the properties of SAEW and found that a decrease in pH accompanied increasing water hardness. From this perspective, water hardness is another crucial factor that has a positive effect on the basic properties of EW and its inactivation efficiency. Pangloli and Hung also reported similar results that water hardness tended to increase the available free chlorine concentration and ORP levels while decreasing the pH of EW. The increase in available free chlorine concentration was probably due to the increase in the concentration of electrolytes and the conductivity which in turn was due to the increase in water hardness”.

The presence of calcium ions (Ca^{2+}), magnesium ions (Mg^{2+}) in water causes the formation of fouling on the cathode (negatively charged electrode) and the forming a milky-colored, solid layer fouling on the cathode reduces the efficiency of the electrode and electrolysis system. Also, the presence of iron ion (Fe^{2+}) in the inlet water causes corrosion because it is oxidized by itself. So, positive ions from the water must be removed. If membrane- or diaphragm-divided cell is used, water purification is very important because water may contain dissolved or undissolved particles. These particles can get stuck in the pores of the membrane or diaphragm and clog it. It reduces the efficiency of electrolysis system. If undissolved particles, such as sand, gravel must be separated, strainer will be used, but if all the hardness from water must be removed, water purification technologies will be used, such as reverse osmosis, ion exchange, activated carbon, electro deionization (EDI) and sub-micron filtration, etc (Filimonova, Received March 21, 2020; revised April 3, 2020; accepted April 10, 2020), (Andrew K. Boal, Spring 2009, Vol. 9, Issue 1), (NaOClean) and (Hyun-Ji Kim, 2019).

Reverse osmosis and ion exchange are the most useable and common technologies to purify water. One of these two types is mostly used in these devices. According to ((ElgaLabWater)), “Reverse osmosis (RO) systems remove pollutants from water including nitrates, pesticides, sulfates, fluoride,

bacteria, pharmaceuticals, arsenic and much more. An RO system, carbon filter will also remove chlorine and chloramines. Reverse osmosis is a cost-effective way to remove impurities from your water through the use of a semi-permeable membrane. Find out how RO removes contaminants. Reverse osmosis (RO) is a process whereby water is passed through a membrane under pressure in cross-flow fashion. With its exceptional purifying efficiency, reverse osmosis is one of the most economical methods for the removal of up to 99% of impurities”.

According to ((ElgaLabWater)), “Ion exchange, as the name suggests, is the exchange of ions between ionized species in the water with ion exchangers, such as H^+ and OH^- ions. The process is reversible and the column can be regenerated by washing through excess ions. Water is passed through beds of ion exchange resins where the ions in solution migrate into the beads. Here, as a function of their relative charge densities (charge per hydrated volume), they compete for the exchange sites. The resins themselves are sub 1 mm porous beads made of highly cross-linked insoluble polymers with large numbers of strongly ionic exchange sites”. Anion-exchange membranes (AEM) must be used in separating water hardness by using ion exchange technology because positive ions (cations) should be removed from water, such as iron ions (Fe^{2+}), calcium ions (Ca^{2+}), and magnesium ions (Mg^{2+}).

There are two main differences between these two technologies (i.e. reverse osmosis and ion exchange): 1. About price: Ion exchange membrane technology is more expensive than reverse osmosis technology, so reverse osmosis is a good economical choice. 2. About the amount of hardness that removed in each technology: In the reverse osmosis technology, all hardness that are smaller than diameter of pores of membrane are separated from water, but in the ion exchange technology, only positive ions, such as magnesium ions, calcium ions and iron ions are separated and negative ions, such as chlorine ions (Cl^-) remain in water and increase the free available chlorine concentration of the hypochlorous acid.

5.2 Quality of Sodium Chloride Salt

Sodium chloride (NaCl) salt is the only chemical solid that is added to the water stream. its purity is very important because the quality of the hypochlorous acid depends on the quality of salt that is used. Also, low-contaminants sodium chloride salt increases the performance of electrolysis system, increases lifespan of device and reduces the need of cleaning and maintenance. One of the reasons that seawater or sea salt is not used in these devices is the presence of a lot of calcium and magnesium in the water, which causes damage to the cell. It is also not economical to separate the total hardness from sea water because the filter of water purification technology fills up very quickly. According to (Andrew K. Boal, Spring 2009, Vol. 9, Issue 1), “Another concern is that some salts contain other chemical species that are subject to oxidation, the most common being bromide (Br^-). In any electrochemical cell that produces chlorine, bromide will be oxidized to form bromates (BrO_3^-)”. Therefore, the amount of hardness and contaminants in the salt should be known, the composition of the required NaCl salt is recommended in the table below (table 5.1) (Andrew K. Boal, Spring 2009, Vol. 9, Issue 1):

Table 2 - 5.1 - The Composition Of Sodium Chloride Salt

Component	Chemical Symbol	Composition
Sodium Chloride	NaCl	More than 99 %
Calcium	Ca	≤ 25 [mg/kg]
Magnesium	Mg	≤ 8 [mg/kg]
Potassium	K	≤ 78 [mg/kg]
Iron	Fe	≤ 10 [mg/kg]
Insoluble Sulphates	SO	≤ 1900 [mg/kg]
Aluminium	Al	≤ 0.01 [mg/kg]
Manganese	Mn	≤ 0.02 [mg/kg]
Copper	Cu	≤ 0.1 [mg/kg]

According to (K. Whangchai) and figure 5.1, higher the amount of salt dissolved in the water, higher the free available chlorine concentration will be existed in the hypochlorous acid. However, the amount of free available chlorine concentration in hypochlorous acid also depends on the residence time of electrolyte solution in electrolytic cell. So, if the electrolyte solution remains in cell for longer time, higher the free available chlorine concentration existed in the hypochlorous acid.

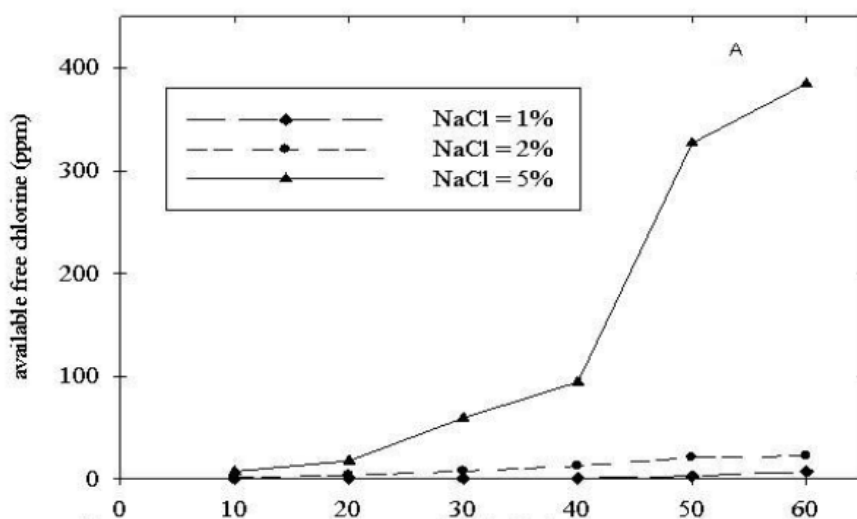


Figure 32 - 5.1 - The Effect of Amount of NaCl Salt on Free Chlorine Available Concentrations in Various time (min)

According to (K. Whangchai) and figure 5.2, this chart examines behavior of the amount of dissolved sodium chloride salt in water at different pH levels. If the electrolyte solution remains in the cell for longer time, the pH level becomes lower and more acidic.

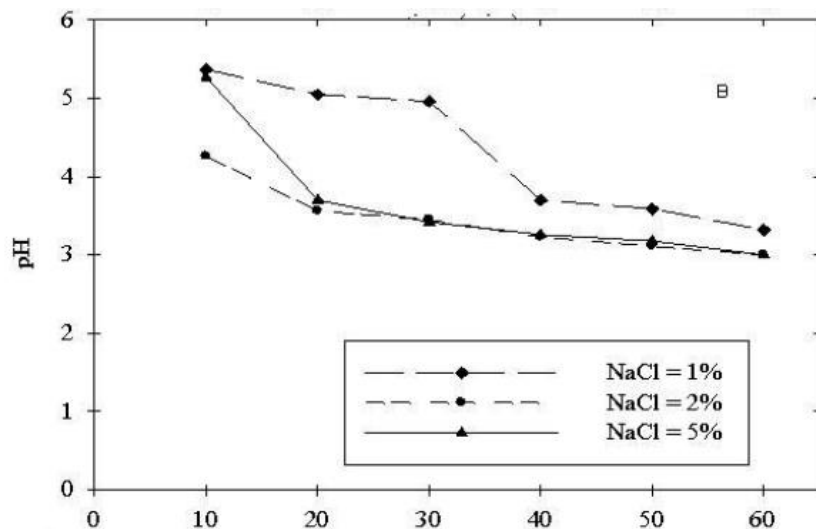


Figure 33 - 5.2 - The Effect of Amount of NaCl Salt on pH in Various time (min)

5.3 pH Control

As is known, the stability, shelf life and effectiveness against viruses of the hypochlorous acid solution highly depends on the pH level. The range between 5 and 7 is very ideal for the pH level of hypochlorous acid because if the pH rises above 7, the majority of free available chlorine converts to hypochlorite ion form and hypochlorous acid is almost unstable. If the pH drops below 5, the majority of free available chlorine converts to chlorine gas and hypochlorous acid is almost unstable. In this pH range, the hypochlorous acid solution has highly effectiveness against bacteria and viruses. Therefore, the pH must be controlled in this range because hypochlorous acid has the highest efficiency and shelf life. One of the possible actions for reducing the pH level of hypochlorous acid that produced in all model of hypochlorous acid generators is reducing the pH level of the feed entering the cell (Khaldoon A. Mourad, 2019), (Daniel L. Joynt, 2015), (Dr.Sohrabi, 2020) and (Libertysprayers).

5.3.1 pH Control for Simple Cells

In simple cells, pH level reduces by some actions that wrote below (Khaldoon A. Mourad, 2019):

- Possible action 1: Reducing the pH level of feed water by reverse osmosis technology or ion exchange technology of water purification**

If the feed water of the electrolytic cell is purified by using reverse osmosis technology or ion exchange technology, it will be reducing the pH level of the feed water. For example, a good reverse osmosis system can reduce the pH of ordinary tap water to range between 5 to 6. Also, using this water purification technology is costly for this model and increases the cost of the devices. Using water purification is not a good economical choice for this model.

- Possible action 2: Reducing the pH level of the feed by adding an acid**

These devices are mostly used for home care devices and acids, such as vinegar (acetic acid) or lemon juice (citric acid) that available at home will be used to reduce the pH level. Adding a certain amount of these acid to brine (water and salt solution), it controls the pH in the reasonable range.

5.3.2 pH Control for Diaphragm-Divided Cells and Membrane-Divided Cells

In divided cells, pH level reduces by some actions that wrote below (Khaldoon A. Mourad, 2019):

1. Possible action 1: Reducing the pH level of feed water by reverse osmosis technology or ion exchange technology of water purification

If the feed water of the electrolytic cell is purified by using reverse osmosis technology or ion exchange technology, it will be reducing the pH level of the feed water. For example, a good reverse osmosis system can reduce the pH of ordinary tap water to range between 5 to 6. In general, these devices use purified water due to the presence of a membrane or diaphragm to remove the water hardness.

2. Possible action 2: Membrane separation

In this method, the pH is controlled in a reasonable range by separating the anolyte and catholyte streams with a diaphragm or membrane. As is known, the pH of anolyte is acidic and the pH of catholyte is alkaline (basic). So, separating anolyte and catholyte helps anolyte to be more stable.

5.3.3 pH Control for Single Cells

In single cells, pH level reduces by some actions that wrote below (Khaldoon A. Mourad, 2019):

1. Possible action 1: Reducing the pH level of feed water by reverse osmosis technology or ion exchange technology of water purification

If the feed water of the electrolytic cell is purified by using reverse osmosis technology or ion exchange technology, it will be reducing the pH level of the feed water. For example, a good reverse osmosis system can reduce the pH of ordinary tap water to range between 5 to 6. In these devices, using the water purification technology is an extra expense. Also, purified water helps to maintain these devices because water hardness damage to the electrolytic cell after a while.

2. Possible action 2: Reducing the pH level of the feed by adding an acid

In general, acid is used in the feed of these devices to control pH level and Usually, hydrochloric acid (HCl) is used. Adding this acid to the system is effective and economical option to reducing the pH level.

3. Possible action 3: Designing the sensing electrode to be close to the protonator electrode

According to (Ian Seymour, 2020), "The local pH at the sensing electrode can be tailored to pH 3 thereby converting all free-chlorine into the hypochlorous acid species. Effective chlorine detection was shown in buffered artificial drinking water samples using in-situ pH control and an enhanced signal response, compared to measurements without pH control, was demonstrated".

5.4 Types and Amount of Feed

5.4.1 Feed of Simple Cells

The feed for these devices generally is ordinary tap water and sodium chloride (NaCl) salt and to reduce the pH level, two acids are mostly used, such as vinegar (acetic acid) and lemon juice (citric acid). The amount of NaCl salt, vinegar or lemon juice and water consumption is different for each devices of simple cells, for example, home care device from the Force of Nature company, it is

needed 3 [gr] of NaCl salt dissolved in 1000 [ml] of water and 5 [ml] of vinegar (Site F. o.) and (SPA, 2018).

5.4.2 Feed of Diaphragm-Divided Cells and Membrane-Divided Cells

The feed for these devices generally is purified water and sodium chloride (NaCl) salt. The amount of NaCl salt and water consumption is different for each devices of divided cells. In general, to produce hypochlorous acid solution with pH level between 2 to 4 by divided cells, the amount of salt dissolved in the water is usually 0.3 - 1 % of total solution (0.3 - 1 % brine) (Ins, 27-Jun-2008), (SPA, 2018) and (Group G.).

5.4.3 Feed of Single Cells

The feed for these devices generally is ordinary tap water, sodium chloride (NaCl) salt and hydrochloric acid (HCl) or ordinary tap water and hydrochloric acid (HCl). The amount of NaCl salt, hydrochloric acid and water consumption is different for each devices of single cells. In general, to produce SAEW by single cells, the electrolyte solution is the mixture of aqueous dilute solution of HCl (3%) and tap water or the mixture of aqueous dilute solution of HCl (6%) and tap water (Angelica Naka, 2020 Feb 18) and (SPA, 2018).

Chapter Six

Quality Criteria and Maintenance

CHAPTER 6 - QUALITY CRITERIA AND MAINTENANCE

6.1 Cell Quality and Maintenance

As is known, the feed of electrolytic cells for producing the hypochlorous acid is mostly water and NaCl salt. After a while, fouling could form on cathode electrode due to the presence of water hardness. If the cell has a divider, such as the membrane and the diaphragm, fouling will form on it due to present of water hardness and also, the pores of divider clogged. In this section, some guidelines for maintaining cell will be reviewed (Corporation B. &., 2010 by John Wiley & Sons):

1. Using purified water instead of ordinary tap water: When purified water is used, the water hardness (i.e. calcium , magnesium, iron) are removed and fouling does not form for a longer time. Also, The electrode and divider are more efficient in this operating condition.
2. Using standard sodium chloride salt that mentioned in the previous chapter instead of high-contaminants NaCl salt: Also, it can delay in the formation of fouling on cathode and divider, but using purified water is more effective because composition of NaCl salt is 0.3 % of feed but also, its purification may increase the quality of the hypochlorous acid in long-term usage.
3. Using new design of electrolytic cells, it designed by Dr. Vitold Bakhir, it is replacing body of the electrochemical cell by cathode; Each electrochemical cell has two or more electrodes, some of them are anodes and some of them are cathodes. The electrodes should be highly conductive and placed in a cell with a non-conductive body, such as ABS or the other material. To increase the surface area of cathodes, anodes could be used same as before and use electrochemical cell with a conductive body as the cathode. Anode should be placed on the center of the electrochemical cell and body of cell should be the cathode and if a membrane or diaphragm is needed, it must be located between the anode and the cathode (the body of the cell). Using this mechanism increases the surface area of the cathode. Also, it increases the time of fouling formation. To prevent of connecting new cathode (conductive body) to the other parts of devices, it can be insulated by a non-conductive cover (Bakhir V.M. D. o.).

Observing these guidelines can helps to maintenance of electrolytic cells but cleaning of the cell is still necessary because the efficiency of any real system is not one hundred percent and therefore, water hardness may still in the water after water purification. So, washing the cell is needed periodically by flushing muriatic acid (hydrochloric acid) to remove the fouling. In general, mixing one part of muriatic acid with eight parts of water can be a strong solution for washing fouling on the cathodes and the divider. Water jet (high pressure) is usually used for flushing water and muriatic acid. The washing time of the cell depends on the capacity of the cell and can take between 15 minutes to a few hours. On average, each cell will need to be cleaned after 4 weeks because fouling reduces the efficiency of the electrolysis system. In single cells (the latest technology for producing the hypochlorous acid), the hydrochloric acid is a part of feed and it could reduce formation of fouling on cathode due to the operation time (Group T.) and (Andrew K. Boal, Spring 2009, Vol. 9, Issue 1).

6.2 Electrodes Quality and Maintenance

Electrodes are the main components of an electrolysis system. As is known, the cathode is negatively charged electrode and attracts cations (positive ions), and the anode is positively charged electrode

and attracts anions. Oxidation reactions occur around the anode electrode and reduction reactions occur around the cathode. The electrodes must have special specifications in electrolytic cells for producing the hypochlorous acid because in these devices, electrodes are in the acidic electrolyte solution which they must have corrosion resistance in acidic solution, for example, aluminum electrodes have high resistance to corrosion and high conductivity and low resistance, but if it is placed in an acidic solution, it will disappear in a very short time. Also, electrode materials have effect on quality of the hypochlorous acid. In general, the electrodes of these devices must have high conductivity to better electrical transmission, low electrical resistance to reduce energy consumption, high resistance to corrosion in acidic solution to longer lifespan, high dimensional stability to does not change the shape of the electrodes and distance between the electrodes. The distance between the electrodes is very important in the electrolysis system and it is different in each device. Spacing between electrode should be the most optimal distance to minimize energy consumption and increase system efficiency. During the process there is no accumulation of charge at any point in the circuit. The theoretical value of current required for depositing a given quantity of metal and the time for which this current should be passed through the electrolyte, it can be calculated from the faraday's laws, if the electrochemical equivalent of the metal is known (Site E. 3.).

As is known, each material of electrodes has different properties, such as corrosion resistance in acidic solution, conductivity, electrical resistance, dimensional stability. In these devices, a wide selection of different electrodes are available, such as titanium coated with platinum, titanium coated with lead dioxide (PbO_2), titanium coated with ruthenium dioxide (RuO_2), titanium coated with tin dioxide (SnO_2), titanium coated with iridium dioxide (IrO_2), titanium coated with mixed coatings of iridium dioxide and ruthenium dioxide and platinum, graphite, lead (Pb), palladium (Pd), stainless steel, copper (Cu), nickel, zinc (Zn), stannum (Sn) and boron-doped diamond (BDD), etc. Also, the material of the electrode has effect on the quality of the hypochlorous acid. The above-mentioned electrodes have been used in hypochlorous acid generators from the past until present, but these electrodes have best efficiency for HOCl generators: titanium coated with mixed coatings of iridium dioxide and ruthenium dioxide and platinum, titanium coated with mixed oxide coatings of iridium and ruthenium. To choose the anode and cathode material, two different materials can be used because only oxidation reactions occur around anode. So, Uncoated titanium or platinum can be used and it is more economical choice than coated electrodes for these devices. However, titanium coated with mixed oxide coatings of iridium and ruthenium has high ability to produce hypochlorous acid with high free chlorine concentration (Reynolds, Received: 13 April 2011 /Accepted: 15 July 2011 /Published online: 2 August 2011 # Springer-Verlag 2011), (Elnathan, May 2012), (Tian Ding, 2019), (Company A.), (Kraft, 2008), (Group T.), (Engineers) and (Guilherme DILARRI, Received 19 Jan, 2016; Accepted 15 May, 2016).

In table 6.1, at temperature of 20 [°C], Conductivity and resistivity of Titanium, platinum, iridium, ruthenium as follows (Site T.) and (Site W. P.):

Table 3 - 6.1 - Resistivity and Conductivity of Common Electrode Materials for Hypochlorous Acid Generators

Material	Resistivity $\rho(\Omega \cdot m)$ at 20°C	Conductivity $\sigma(S/m)$ at 20°C
Titanium	5.56×10^{-7}	1.798×10^6
Platinum	1.06×10^{-7}	9.44×10^6
Iridium	5.289×10^{-8}	1.891×10^7
Ruthenium	7.595×10^{-8}	1.31×10^7

According to (Alexander Kraft), “The AQUADES-EL system has been produced and distributed since 1998 by the German companies Aqua Rotter GmbH and G.E.R.U.S mbH. More than 400 systems have been sold and installed in hotels, hospitals, barracks, retirement homes and other buildings. Figure below (figure 6.1) shows the AQUADES-EL device. It employs **titanium electrodes coated with mixed IrO_2/RuO_2** . An advanced control system measures the free chlorine concentration in the water at several locations in the distribution system at regular time intervals by amperometric detection”.



Figure 34 - 6.1 - Electrochemical Disinfection Device AQUADES-EL

6.3 Monitoring and Control System

Control systems are the technologies that recently has been used in electrolytic cells for producing the hypochlorous acid to increase the quality and stability of it, a programmable logic controller (PLC) usually used for this purpose. These control systems have three main parts, the software part and two hardware parts (monitoring and controlling parts). The mechanism of these controllers is that the hardware part (i.e. temperature sensors, pressure sensors, pH sensors and conductivity sensors, etc.)

monitoring the properties of the final product (hypochlorous acid solution) and it sends a signal to the software part. In the software part, this signal is checked and finally converted into a control signal that it changes controlling hardware part parameters (such as flow valves, pressure regulators, mixer of salt and water, current and voltage, etc.) to reach the ideal properties for final product. The software part can be run on different computers and also, it can be stored on different memory devices. According to (Daniel P. Longhenry (Bloomington, 2014), “Any computer-readable memory device can be used, such as a disc drive, a solid-state drive, CD-ROM, DVD, flash memory, RAM, ROM and a set of registers on an integrated circuit, etc. For example, the control circuit can be implemented partly or completely in a programmable logic controller and/or a processing device, such as a microcontroller and/or other processor that executes instructions stored in a memory device, wherein the instructions are configured to perform the steps of the control process when executed by the processor device to convert the processing device into a special purpose computer”.

Chapter Seven

Economic Review

CHAPTER 7 - ECONOMIC REVIEW - ECONOMIC AND COMMERCIAL CONSIDERATIONS

Hypochlorous acid is a cost-effective disinfectant solution because feed of these cells is only water, sodium chloride salt and electricity or water, NaCl salt, Hydrochloric acid and electricity. According to (BWT group), “Nowadays, roughly 48 million tons of chlorine are produced each year, with more than 30% of this sum being converted by membrane electrolysis. Furthermore, membrane electrolysis is applied for the production of sodium hypochlorite for drinking water disinfection. Recently, electrolysis processes for the production of ozone, chlorine dioxide or hypochlorous acid have been increasingly applied in drinking water disinfection”.

According to Chapter 4, there are four different types of electrolytic cells for the producing the hypochlorous acid. These cells are used according to their required applications. **Simple cells** are the simplest cells to produce HOCl and are very cheap, it mostly used for home care and operates batch so produces small volumes. In divided cell, **diaphragm-divided cells** are not common today and **membrane-divided cells** are more common at the present, which are updated model of divided cell by diaphragm. As is known, these cells produce two products and are mostly used in hospitals and centers that use both products for disinfectants. These are most expensive models for producing HOCl and operates continuously. **Single cells** are the latest technology in the production of HOCl and their product is only hypochlorous acid, these devices are expensive but they have lower price than divided cell by membrane. They operate continuously and produce the large amount of HOCl per hours.

According to Appendix B, These devices have different prices, for **simple cells** devices, the price is between \$ 120 and \$ 300. **Single cells** devices are priced between \$ 7,200 and \$ 30,000. **Membrane-divided cells** are priced between \$ 25,000 and \$ 45,000. As is known, the material used for the electrodes, the body of cell and the cabin, volume that these devices can produce per hour have effect on total price of device. However, ability to produce more volumes per hours can increase price of device. If more information is needed, technical, economic details for HOCl generators is readily available in appendix B.

About the other costs, **simple cells** do not need an operator and have not maintenance costs, but **single cells and divided cells** have maintenance costs and require operators. Membrane-divided cells have higher maintenance cost because membrane maintenance is very difficult and expensive. Also, single cells and divided cells need to installation and setup. In these models (Single cells and membrane-divided cell) of devices, the price mentioned above is only price for the cell, its components (i.e. electrodes, divider), controller and power supply (battery or AC/DC converter), and the cost of setting up and installing devices and piping are added to the cost of the device for total price of hypochlorous acid production unit. In general, one of the most important parameters of a plant is the space required for devices. So, the smaller cabin of the device is more efficient. In the appendix B, the weight and dimensions of the devices are readily available. According to response from Aquaiox company (Appendix D), the cost of installation these devices is \$ 5000, but according to response from Dinol company (Appendix D), this cost is between \$ 10 to \$ 15. This cost depends on various parameters of the device, such as electrode material, power consumption, pressure required for the device, material of cell, volume (capacity) of the device, pipes sizing required for the device, mode of

operation (batch or continuous), type of fittings, type of salt mixer and type of pump. On average, the invested cost will be returned within a year (Fera R. Dewi, 2017 March 10).

Industrially, when only hypochlorous acid is needed, single cells are more efficient devices and the hypochlorous acid that produced from this model has a longer shelf life. If hypochlorous acid and sodium hydroxide are needed, membrane-divided cells are more efficient devices. Simple cells are not industrial models for producing hypochlorous acid at all and this model is very economical and common for home care use.

Chapter Eight

Conclusions

CHAPTER 8 - CONCLUSIONS

The present study attempted to investigate the applicability of the electrolytic cells (type of electrochemical cell) in produce the hypochlorous acid (HOCl) and what types of electrolytic cells are used to produce HOCl. Determine the effects of various operating parameters on stability and effectiveness of hypochlorous acid, such as salt consumption, quality of water, quality of salt, pH levels, voltage, current density, temperature of electrolyte, mode of operating (i.e. batch and continuous process), residence time of the hypochlorous acid in electrolytic cell, kind of electrodes, electrodes material and types of electrolytic cells, etc. Using different model of cells was affected by different types of parameters of HOCl, such as pH level, shelf life, FAC concentration, ORP, conductivity.

Hypochlorous acid (HOCl) is known as a very useful disinfectant solution. The effectiveness of HOCl depends on the free available chlorine concentration. If FAC concentration is higher than 500 [ppm], it could damage and irritation on skin, but it is much more effective and completely safe for humans in lower free chlorine concentrations and has many disinfecting applications, such as agriculture sanitization, hospital cleaning, hand Sanitization, mouth and teeth disinfection, etc. Also, the stability and shelf life of hypochlorous acid highly depends on the pH level. Each model of electrolytic cell for hypochlorous acid, produces hypochlorous acid with different pH level. So, hypochlorous acid solution classified into three categories according to the level of pH: **1.** Natural electrolyzed water (7 - 8) **2.** Slightly acidic electrolyzed water (5 - 6.5) **3.** Acidic electrolyzed water (2.5 - 3.5). Slightly acidic electrolyzed water is more stable than other form of hypochlorous acid solution because in this range of pH, hypochlorous acid is mostly existed.

The optimal operating condition for producing HOCl depends on model of electrolytic cells. According to the divider between the electrodes, a spectrum defined for all models of electrolytic cell. One side of this spectrum is no divider between the electrodes and its point is zero. About the other side, the location of the divider without any pores is point one. There are dividers between these two points that have pores. The divider with small pore size, closer to point one and vice versa. Also, the divider with smaller pores size can prevent to mixing of fluid efficiently and two streams will be produced. The product of the anode chamber is called the anolyte and contains a variety of oxidants, including hypochlorous acid, singlet oxygen, peroxide anion, superoxide, ozone, monoatomic oxygen and free radicals, known to possess antimicrobial properties. The product of the cathode chamber is called the catholyte, catholyte is a by-product in this process because it is a secondary product derived from a production process of hypochlorous acid and mostly contains sodium hydroxide (NaOH). If there isn't any divider between electrodes, it will produce hypochlorous acid, water, chlorine ion, hypochlorite, hydrochloric acid in electrolyte solution.

In this study, There are four electrolytic cells for producing hypochlorous acid according to the divider between the electrodes. According to spectrum defined above, simple cells and single cells are exactly located at the zero point because they haven't any dividers and produces only hypochlorous acid. Diaphragm-divided cells are located approximately between point one and zero, probably located at $\frac{1}{2}$ or upper because the size of diaphragm pores is relatively larger than pores of membrane and also, membrane-divided cells are located closer to point one.

The feed of these cells is mostly water and sodium chloride (NaCl) salt. Although, for better controlling pH level of hypochlorous acid solution in newer systems, the device's feed is water, NaCl salt and Hydrochloric acid (HCl) or water and Hydrochloric acid. As is known, stability of hypochlorous acid depends on pH level. To control pH level, a control system is needed to optimize pH level of electrolyte. In single cells, pH level of electrolyte controlled in range 4 to 7 but in divided cells, pH level of anolyte controlled in 2 to 4 and it controlled for catholyte in 11 to 13. Also, high temperature and pressure can damage to electrolytic cell and so, temperature and pressure of feed must be controlled.

In cells divided by diaphragm or membrane, quality of water and salt is important as feed of generators. So, water and salt must be purified because hardness, such as calcium, iron, magnesium and other hardness causes formation of fouling on the cathode electrodes and divider. If these hardness get stuck in the divider, it decreases its efficiency. It will cause the reducing of current and so, consumption of supply power will increase and efficiency of whole of device will be decreased.

In general, these devices have some problems. Main problems in these devices as follows:

1. Fouling on cathodes and divider
2. Corrosion on anode
3. Low shelf life of the hypochlorous acid

Chapter Nine

Recommendations

CHAPTER 9 - RECOMMENDATIONS

My recommendation are as follows:

1. In relation to best device that could produce hypochlorous acid

It was recommended that a divided cell by using dual ion-exchange membrane is very efficient device and also produces hypochlorous acid with higher shelf life and sodium hydroxide as a by-product. This device has three different electrolysis chambers and generates functional electrolyzed water of pH 2.7 ~ 12 excluding salt (NaCl) which is used as an electrolyte through the special membrane which can divide salt (NaCl), electrolyte, into Na^+ ion and Cl^- ion completely. Anolyte produced in anode chamber and catholyte produced in cathode chamber, the middle chamber is location for feed entering. This device is expensive because the present of dual membrane but it is the best system for producing hypochlorous acid. In this device, the pH is reduced with a small slope compared to divided cells by one membrane and therefore, the produced hypochlorous acid solution has the properties of produced hypochlorous acid from single cell. In addition to hypochlorous acid, sodium hydroxide is also produced as a by-product, it is very useful for various industries.

2. In relation to corrosion on anode

As is known, corrosion on the anode is one of the main problems that could be occur in these devices because oxidation reactions be accomplished around anode and this issue can reduce its efficiency. Two different materials can be used for the anodes and cathodes because oxidation reactions only occur around the anode, and only the anode must be corrosion resistance. It was recommended that titanium electrode coated with mixed coatings of iridium dioxide and ruthenium dioxide and platinum can be used for anode and for cathode, pure titanium can be used and pure platinum is not very useful because it is very expensive.

3. In relation to fouling formation on the cathode in electrolytic cells

At the present, to prevent the formation of fouling on cathode electrodes and divider in divided cells, the inlet water must be purified and hardness that cause fouling are removed from it by reverse osmosis water purification technology or ion-exchange water purification technology. In this case, it was recommended that it is better to use the reverse osmosis technology because it removes all the water hardness and has cheaper price than ion-exchange water purification. One the application of hypochlorous acid is fogging by ultrasonic fogger for disinfection of indoor environments. If these hardness are not separated from water, they stuck in human lungs during the fogging process and cause the shortness of breath. Also, water hardness causes the fouling on cathode electrodes and divider, it can be reducing its efficiency on electrolytic cells.

4. In relation to spacing between electrodes

Spacing between electrodes is a very important factor in electrochemical cells. This distance must be optimized by using faraday's law. It was recommended that modeling electrolytic cell by solidworks simulation software is very efficient and final data for electrolytic cell factors

could be generate from this simulation software. In solidworks software, cells can be designed into 3D geometry.

5. In relation to low shelf life of the hypochlorous acid

Many companies controlled the pH level of the hypochlorous acid between 5 to 7. These company recommend that the hypochlorous acid produced during this range of pH has more stability and shelf life. However, It was recommended that according to figure 2.2, hypochlorous acid is most stable in the pH levels between 4 to 6. If pH level of the hypochlorous acid controlled in this range, it will be extended the shelf life of the HOCl.

6. In relation to DC current power supply

DC current power supply is one of the most important components of the electrolytic cells and electrolysis process is impossible without DC current power supply. In some cases, may hypochlorous acid solution is needed as sanitizer agent and it is impossible to produce HOCl due to the lack of electricity supply. In these situations, it was recommended that photovoltaic solar panels can be used. Photovoltaic (PV) panels are part of renewable energy devices and they use sunlight as a source of energy. So, electrolytic cells can produce hypochlorous acid by using generated electricity from photovoltaic panels. Also, photovoltaic panels generate electricity with DC current and there is no need to convert it to AC current power supply because electrolytic cells also need DC current power supply.

7. In relation to water temperature

The temperature of the water entering the electrolytic cells is also one of the important factors and if the water temperature is out of mentioned range, it will cause damage to the electrolytic cell. If the water temperature is lower than 4.5 [°C], It was recommended that using the unglazed panels to heat the water. Unglazed panels are the easiest and green way to rise the water temperature to 10 degrees and they are part of renewable energy devices. These panels are placed on the roof and increase the water temperature by receiving energy from the sun. By using unglazed panels, the water temperature can be set in the mentioned range for the water temperature and so, there is no damage to the electrolytic cells.

8. In relation to control system

In newer electrolytic cells for the producing the hypochlorous acid, control systems are used to control the input parameters of the cells for increasing the quality of product. It was recommended that using the control system to change the flow rate of inlet stream (feed stream). In fact, a control valve installed on the feed stream pipeline to increase and decrease the flow rate of the inlet feed. Decreasing the flow rate of feed stream increases the residence time of the electrolyte solution in the cell and increasing the residence time increases the quality of hypochlorous acid solution. This control system monitoring the properties of product and increases or decreases the input feed flow rate that the product reaches the desired quality.

Chapter Ten

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CHAPTER 10 - REFERENCES

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Chapter Eleven

Appendices

CHAPTER 11 - APPENDICES

11.1 Appendix A - Some Companies That Supply HOCl Generators and Their Contact Information

These hypochlorous acid generators are produced in some countries, such as Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Iran, Japan, Malaysia, Mexico, North America, Philippines, Russia, Saudi Arabia, South Korea, Taiwan, USA and Vietnam.

Companies information is as follows:

1. **A Better Way**
Home Page : <https://abetterwaydistributing.com/>
Contact Email : info@abetterwaydistributing.com
2. **AKUA.Kr**
Home Page : <http://www.akua.kr/>
Contact Email : h2o@akua.kr
3. **ANOLYTECH.SE**
Home Page : <https://www.anolytech.se/en/about-anolytech/>
Contact Email : info@anolytech.se
4. **ANSQUA**
Home Page : <http://www.anaqua-concept.com/>
Contact Page : <http://www.anaqua-concept.com/contact.php>
5. **AQ Group**
Home Page : <https://www.aqgroup.nl/>
Contact Email : info@aqinternational.be
6. **Aqua steel**
Home Page : <https://aquasteel.co.uk/>
Contact Email : sales@bayer-wood.co.uk, laura@bayer-wood.co.uk
7. **Aqua Tech**
Home Page : <https://www.aquatech.com/>
Contact Email : aic@aquatech.com, csg@aquatech.com
8. **AQUAECA**
Home Page : <http://aquaeca.com/>
Contact Email : aquaeca@gmail.com
9. **AQUALUTION**
Home Page : <https://www.aqualution.co.uk/>
Contact Email : info@aqualution.co.uk
10. **AQUAOX**
Home Page : <https://www.aquaox.com/>
Contact Email : info@aquaox.net
11. **AQUOX**
Home Page : <https://aquox.in/>
Contact Email : sales@aquox.in, care@aquox.in
12. **Astral Pool**

Home Page : <https://www.astralpool.com/>

Contact Page : <https://www.astralpool.com.au/contact>

13. ATOM PLUS (tablet)

Home Page : <http://atomplus.co.za/>

Contact Email : ed@atomplus.co.za, guy@atomplus.co.za

14. AVKARE

Home Page : <https://www.avkare.com/>

Contact Email : drugsafety@avkare.com

15. BAKHIR & ECT

Home Page : <http://vb institute.org/about/>

Contact Email : eca@vb institute.ru, vitold@bakhir.ru

16. Blue Sense

Home Page : <https://www.bluesense-water.com/>

Contact Email : info@mezutec.nl, info@nsa-composants.fr, info@hsd-water.com

17. Briotech

Home Page : <https://www.briotechusa.com/>

Contact Email : info@briotechusa.com

18. Cantex

Home Page : <https://www.cantexinc.com/>

Contact Email : haven't any email

19. CHEMNIUM

Home Page : <https://www.chemnium.com/>

Contact Email : info@chemnium.com, chemnium@gmail.com

20. Chlorking

Home Page : <https://www.chlorking.com/>

Contact Email : info@chlorking.com

21. Clean Water

Home Page : <https://www.cip-cleanwater.eu/en/home>

Contact Email : info@cip-cleanwater.eu

22. CONTROLOMATIC

Home Page : <https://www.controlomatic.com/>

Contact Page : <https://www.controlomatic.com/contact-us/>

Contact Email : sales@controlomatic.com

23. Danish Clean Water

Home Page : <https://danishcleanwater.com/>

Contact Email : info@danishcleanwater.dk

24. Danolyte

Home Page : <https://danolyte.co/>

Contact Email : Accounting@DanolyteGlobal.com

Marketing Email : Marketing@DanolyteGlobal.com

25. Denora

Home Page : <https://www.denora.com/>

Contact Email : info.idn@denora.com

26. Dinol

Home Page : <https://www.di-nol.com/>

Contact Email : dinore@126.com

27. Dioxide PACIFIC

Home Page : <https://www.dioxide.com/>

Contact Email : sales@dioxide.com, saleswa@dioxide.com, salesvic@dioxide.com,
salesus@dioxide.com, service@dioxide.com

28. Disinfection Squad

Home Page : <https://www.disinfectionsquad.com/>

Contact Page : <https://www.disinfectionsquad.com/contact>

29. Duerr Dental

Home Page : <https://www.duerrdental.com/en/home/>

Contact Email : info@duerrdental.com

30. EAQUASYS

Home Page : <https://eaquasys.com/>

Contact Email : info@eaquasys.com

31. EAU Tech

Home Page : <https://www.eautechnologies.com/>

Contact Email : info@eautechnologies.com

32. ECA Sanitizer

Home Page : <https://ecasanitizer.com/>

Contact Email : info@ecasanitizer.com

33. ECA Tech

Home Page : <https://ecatech.co.za/>

Contact Email : info@ecatech.co.za

34. Eco From

Home Page : <http://www.ecofrom.co.kr>

Contact Email : eco@ecofrom.co.kr, eco61@naver.com

35. Eco Logic Solutions

Home Page : <http://ecologicsolutions.com/>

Contact Email : info@ecologicsolutions.com

36. Ecolife

Home Page : <http://www.ecolife.com/>

Contact Page : <http://www.ecolife.com/contact.html>

Contact Email : admin@ecolifeconservation.org

37. Ecolox Tech

Home Page : <https://ecoloxtech.com/>

Contact Page : <https://ecoloxtech.com/contact-us/>

Contact Email : service@ecoloxtech.com

38. Eight Tech

Home Page : <https://www.eight-tech.com>

Contact Email : info@eight-tech.com

39. Electrox Water

Home Page : <https://www.electroxwater.co.uk/>

Contact Email : sales@electroxwater.co.uk

40. Ennore India

Home Page : <http://ennoreindiachemical.com>

Contact Email : info@ennroeindiachemical.com

41. Enviroch

Home Page : <http://www.enviro-chem.com>

Contact Email : enviroch@monsanto.com

42. Envirolyte

Home Page : <http://www.envirolyte.com/>

Contact Email : envirolyte@envirolyte.com

43. Environize

Home Page : <https://www.environize.ca/>

Contact Email : info@environize.ca

44. Excel Test

Home Page : <http://www.exceltest.com.my/>

Contact Email : exceltest@excelonez.net

45. Force of Nature

Home Page : <https://www.forceofnatureclean.com/>

Contact Email : support@forceofnatureclean.com

46. FumaTech

Home Page : www.fumatech.com

Contact Email : info@fumatech.com

47. Geemblue

Home Page : <https://www.geemblue.com/>

Contact Email : info@geemblue.com

48. GenEon's

Home Page : <https://www.geneontechnologies.com/>

Contact Email : servicegeneon@triadservice.com, service@geneontech.com

49. Genox

Home Page : <http://clearwater.eu.com/>

Contact Email : alex.winter@wcs-group.co.uk

50. Germ kill 365

Home Page : <https://germkill365.com/>

Contact Email : CRAIG@GERMKILL365.COM

51. Hangzhou Meimei Technology Co

Home Page : <http://www.hzmmkj.com/en/>

Contact Email : hzmmkj@163.com

52. HES Water Engineers

Home Page : <http://hesweindia.com/index.php>

Contact Email : hesweindia@hesweindia.com, waterengineersindia@gmail.com

53. HOSHIZAKI

Home Page : <https://www.hoshizaki.co.jp/>

Contact Email : haven't any email

54. Hypochlorous Acid

Home Page : <https://www.hypochlorousacid.com/about>

Contact Email : haven't any email

55. Hypochlorous acid cell

Home Page : <https://hypochlorousacidcell.com/>

Contact Email : info@hypochlorousacidcell.com

56. HypoGen

Home Page : <http://hypogen.com/contact.php>

Contact Email : info@hypogen.com

57. Inmito

Home Page : <https://www.inmito.com/>

Contact Email : info@inmito.com

58. Innova Global

Home Page : www.innovaglobal.com

Contact Email : dkhorram@innovaglobal.com

59. IQ Green Solutions

Home Page : <https://iq-greensolutions.com/>

Contact Email : info@iq-greensolutions.com

60. IZUMRUD

Home Page : <http://www.izumrud.com.ru/>

Contact Email : izumrud@aquaecca.ru

61. KAIYU

Home Page : <https://kaiyuco.com/en/contact/>

Contact Email : info@kaiyuco.com

62. Kanghui water

Home Page : <http://www.kanghuiwater.com/en/index.asp>

Contact Email : sd-kanghui@163.com

63. Kemisan

Home Page : <https://www.kemisan.com/en/about-us>

Contact Email : info@kemisan.com.tr, kemisan@kemisan.com.tr

64. Kingdom Chemical

Home Page : <https://kingdom-chemical.com/>

Contact Email : Chad@kingdom-chemical.com

65. Kirk Mayer

Home Page : <https://www.kirkmayer.com/company/>

Contact Email : info@kirkmayer.com

66. Koken

Home Page : <https://www.koken-ltd.co.jp/english/>

Contact Page : <https://www.koken-ltd.co.jp/english/inquiry/>

67. KTTC

Home Page : <http://medicleanatoz.com/>

Contact Email : h2o@akua.kr

68. LEAUS

Home Page : <http://leaus-bio.com/>

Contact Email : info@leaus-bio.com

69. LENN TECH

Home Page : <https://www.lenntech.com/>

Contact Email : info@lenntech.com

70. Max Assure

Home Page : <https://max-assure.com/>

Contact Email : haven't any email

71. Medcare supply

Home Page : www.medcaresupply.com

Contact Email : info@medcaresupply.com

72. Medipure

Home Page : <http://www.medipure.co.uk/suprox>

Contact Email : helpdesk@medipure.co.uk, enquiries@medipure.co.uk

73. MIOX

Home Page : <https://www.miox.com/>

Contact Email : support@miox.zendesk.com

74. MiracleIN Corporation

Home Page : http://www.miraclein.com/eng_index.php

Contact Email : servant@miraclein.com

75. NaOClean

Home Page : <http://www.naoclean.com/>

Contact Email : dndeale@dndeale.com

76. Neukocyte

Home Page : <http://neukocyte.com/>

Contact Email : neukocyte.hclo@gmail.com

77. NMT

Home Page : <http://www.nmtlimited.com/>

Contact Email : gasinee_ch@minor.com

78. NOBLE CHLOR ECO

Home Page : <http://www.noblechlor.com/>

Contact Email : sales@noblechlor.com, om@noblechlor.com

79. OSG Corporation

Home Page : <http://www.osg-corp.com/english/>

Contact Page : <http://www.osg-corp.com/english/contact/>

80. pHur Water

Home Page : <https://phurwater.com/>

Contact Page : info@pHurwater.com

81. Pristine Water

Home Page : <https://pristinewater.in/>

Contact Email : sales@pristinewater.in, support@pristinewater.in

82. ProMinent

Home Page : <https://www.prominent.com/en/>

Contact Email : info@prominent.com

83. Pure & Clean

Home Page : <https://pureandclean.us/>

Contact Email : info@pureandclean.us

84. PUR-HOCl (tablet)

Home Page : <https://www.pur-hocl.eu/>

Contact Email : kontakt@pur-hocl.eu

85. Radical Waters

Home Page : <https://www.radicalwaters.com/about-us/>

Contact Email : info@radicalwaters.com

86. Saffrongrid limited

Home Page : <https://www.indiamart.com/saffrongrid/>

Contact Page : <https://www.indiamart.com/saffrongrid/enquiry.html>

Contact Email : info@sgrid.in, sales@sgrid.in

87. Sidal Saglik

Home Page : <https://www.sidal.com.tr/index-en>

Contact Email : info@sidal.com.tr

88. SION TECH

Home Page : <http://www.siontech.com/>

Contact Email : namdcho@siontech.com

89. Stearnspkg

Home Page : <https://www.stearnspkg.com/>

Contact Email : contact@stearnspkg.com

90. Sterilex

Home Page : <https://www.sterilex.com/>

Contact Email : alex.josowitz@sterilex.com, faith.insley@sterilex.com,
bob.forner@sterilex.com

91. Sterilez

Home Page : <http://www.sterilezz.com/>

Contact Email : hcsco88@gmail.com

92. Superaqua

Home Page : <https://www.superaquaholding.com/>

Contact Email : superaqua8899@gmail.com

93. TAEYOUNG E&T

Home Page : <http://www.tyentgroup.com/>

Contact Email : haven't any email

94. Tech Briefs

Home Page : <https://contest.techbriefs.com/about>

Contact Page : <https://contest.techbriefs.com/contactus>

95. The Clorox

Home Page : <https://www.thecloroxcompany.com/>

Contact Email : investorrelations@clorox.com, supplier.diversity@clorox.com

96. The institute of occupational safety and health

Home Page : <https://iosh.com/>

Contact Email : csc@iosh.com, reception@iosh.com

97. Tianno

Home Page : <http://www.tiaano.com/>

Contact Email : dsamktg@tiaano.com, dsa@tiaano.com

98. TURI

Home Page : <https://www.turi.org/About>

Contact Email : ellenbec@turi.org, chris@turi.org

99. TU-SEIKI

Home Page : <https://diengiainhatban.com/>, <https://tu-seiki.com/>

Contact Email : hotro@diengiainhatban.com

100. UltraPure

Home Page : <https://ultrapurehocl.com/>

Contact Email : product@ultrapuregreen.com

101. UNIDO

Home Page : http://www.unido.or.jp/en/about_us/

Contact Page : <https://www.unido.or.jp/en/contact/>

102. VDH Water Technology

Home Page : <https://www.vdhwater.com/>

Contact Email : info@vdhwater.nl

103. Viking Pure

Home Page : <https://vikingpure.com/>

Contact Email : haven't any Email

104. Winter National

Home Page : <http://www.wtinternational.ma/en/>

Contact Email : info@wtinternational.ma

105. Xtreme Bioclean

Home Page : <https://www.xtremebiocleansolutions.com/>

Contact Email : customerservice@xtremebiocleansolutions.com

106. ZGEN

Home Page : <https://zgenhocl.com/>

Contact Page : <https://zgenhocl.com/>

107. Zibo horizon Environmental Technology

Home Page : <http://www.sdhanhong.com/en/>

Contact Email : zbhanhong@163.com

108. گروه خسرو مدیسا طب

Home Page : <https://www.kmtmed.com/>

Contact Email : contact@kmtmed.com

109. مهار فن ابزار

Home Page : <https://maharfanabzar.com/>

Contact Email : info@maharfan.com

11.2 Appendix B - Technical and Economic Details of Hypochlorous Acid Generators

Company Name (Brand)		Ecolox Tech	OSG Corporation	OSG Corporation
Product Name		EcoloxTech1200/240	NDX-1500PLB	NDX-70KMW
Dimensions (L*W*H)	[cm]	35*24*52 / 32*17*42	80*55.3*127.5	27.7*27.7*34.8
Weight	[kg]	21.2 / 11.8	N/A	9.5
Power Supply		AC 110/220V 50/60 Hz	AC100V 50/60Hz	AC100V 50/60Hz
Ampere	[Amp]	20 - 65	4.4	3
Recommended capacity (storage tank)	[l]	N/A	1500	72
Electrolysis Type		Single Cell	N/A	N/A
Material of devices		Stainless Steel	N/A	N/A
Mode of Working		Continuous	N/A	Continuous
Pressure Range Allowable	[bar]	<3.5	2.5 - 7.5	N/A
Flow Rate of Product	[l/hr]	N/A	1500	72
Water Working Temperature	[°C]	10 - 30	5 - 35	0 - 35
NaCl Consumption	[g/hr]	N/A	N/A	N/A
Types of Products		Only Hypochlorous acid	N/A	N/A
ORP	[mV]	> 1000 mV	N/A	N/A
Barrier Between Electrodes		N	N/A	N/A
Available Chlorine Concentration	[ppm]	10 - 400 / 10 - 200	100 - 200 or 50 - 100	50 - 80
pH Range	[pH]	5 - 8	4.5 - 7.8	4 - 6
Electrodes Material (lifespan)		N/A	N/A	N/A
HOCl Production Controller		pH Controller	pH measuring device	N/A
Price	USD	7249 - 33540	N/A	N/A
N/A = Not Available N = Nothing				

Company Name (Brand)		Taeyoung E&T Co	HOSHIZAKI	HOSHIZAKI
Product Name		TIE-T3H/T5H/T10H	ROX-20TA-U	ROX-15SA
Dimensions (L*W*H)	[cm]	47.1*42*65.7 / 42*35*149 / 42*35*149	400*280*310	140*65*180
Weight	[kg]	28 / 55 / 60	20	120
Power Supply		AC100~120V, 200~240V 50~60Hz	AC115 50~60Hz	AC100 50~60Hz
Ampere	[Amp]	N/A	2.7	3 – 11.4
Recommended capacity (storage tank)	[l]	150 / 300 / 500	180 - 240	200
Electrolysis Type		Non-Diaphragm	Cell Divided	Cell Divided
Material of devices		Stain Steel	N/A	N/A
Mode of Working		N/A	N/A	N/A
Pressure Range Allowable	[bar]	N/A	1 - 7.8	1.5 - 7.5
Flow Rate of Product	[l/hr]	150 / 300 / 500	180 - 240	Alkaline Water: 90 Acidic Water: 90
Water Working Temperature	[°C]	N/A	5 - 30	5 - 30
NaCl Consumption	[g/hr]	N/A	N/A	N/A
Types of Products		Only Hypochlorous acid	Alkaline Water (NaOH), Acidic Water (HOCl)	Alkaline Water (NaOH), Acidic Water (HOCl)
ORP	[mV]	N/A	N/A	N/A
Barrier Between Electrodes		N	N/A	N/A
Available Chlorine Concentration	[ppm]	10 - 30	N/A	N/A
pH Range	[pH]	5 - 6.5	N/A	N/A
Electrodes Material (lifespan)		N/A (5000 hr)	N/A	N/A
HOCl Production Controller		N/A	Acidic / Alkaline Test Papers, Chlorine Test Papers cup	Acidic / Alkaline Test Papers, Chlorine Test Papers
Price	USD	N/A	N/A	N/A

Company Name (Brand)		Super Aqua	GEEMBLUE	PRISTINE WATER
Product Name		Golden Alkalizer GA-3000	GBM-200L-HCLO	HypoGen 10/25/50/100/200/400
Dimensions (L*W*H)	[cm]	84.3*64*124	N/A	N/A
Weight	[kg]	250	N/A	N/A
Power Supply		AC220V (3-phase)	AC220V 50 Hz	N/A
Ampere	[Amp]	50	N/A	N/A
Recommended capacity (storage tank)	[l]	N/A	N/A	100 / 300/ 500 / 1000 / 2000 / 4000
Electrolysis Type		Cell Divided	Cell Divided	Undivided Cell
Material of devices		N/A	ABS	N/A
Mode of Working		Continuous	N/A	Batch
Pressure Range Allowable	[bar]	2 - 2.5	N/A	N/A
Flow Rate of Product	[l/hr]	4000 (Alkaline Water: 3000, Acid Water: 1000)	Acidic Water: 200	N/A
Water Working Temperature	[°C]	N/A	N/A	N/A
NaCl Consumption	[g/hr]	N/A	N/A	N/A
Types of Products		Alkaline Water (NaOH), Acidic Water (HOCl)	Alkaline Water (NaOH), Acidic Water (HOCl)	Only Hypochlorous Acid
ORP	[mV]	Alkaline: -100 ~ -300	N/A	N/A
Barrier Between Electrodes		N/A	Imported Polymer Membrane	N
Available Chlorine Concentration	[ppm]	N/A	50 - 60	500
pH Range	[pH]	Alkaline: 7 - 10 Acid: 4 - 7	Alkaline: 10 - 12 Acid: 5 - 6.5	N/A
Electrodes Material (lifespan)		(6000 hours)	Titanium with Ruthenium, Iridium and Platinum coating	N/A
HOCl Production Controller		pH Controller	N/A	N/A
Price	USD	45,000	Negotiation	N/A

Company Name (Brand)		GEEMBLUE	GEEMBLUE	GEEMBLUE
Product Name		GBH-10L-HCLO /50/100/200/300	GBS-40-HCLO	GBS-400-HCLO/ 800
Dimensions (L*W*H)	[cm]	N/A	42*35*100	N/A
Weight	[kg]	N/A	25	N/A
Power Supply		N/A	AC220V 50 Hz	AC220V 50Hz
Ampere	[Amp]	N/A	N/A	N/A
Recommended capacity (storage tank)	[l]	N/A	N/A	N/A
Electrolysis Type		N/A	Single Cell	N/A
Material of devices		N/A	MDF	N/A
Mode of Working		Continuous	Continuous	N/A
Pressure Range Allowable	[bar]	N/A	N/A	N/A
Flow Rate of Product	[l/hr]	10 / 50 / 100 / 200 / 300	40	400 / 800
Water Working Temperature	[°C]	N/A	N/A	N/A
NaCl Consumption	[g/hr]	N/A	N/A	N/A
Types of Products		Only Hypochlorous Acid	Only Hypochlorous Acid	Only Hypochlorous Acid
ORP	[mV]	N/A	N/A	N/A
Barrier Between Electrodes		N	N	N
Available Chlorine Concentration	[ppm]	200	70	100 - 200
pH Range	[pH]	2.7 - 6.5	6.5 - 7.5	2.7 - 3.5
Electrodes Material (lifespan)		N/A	N/A	N/A
HOCl Production Controller		N/A	PLC	N/A
Price	USD	Negotiation	Negotiation	Negotiation

Company Name (Brand)		UNIDO	SION TECH	Dinol
Product Name		KEW-A009-1A/2A/3A	SDI-C2/C4	Dinol Customized
Dimensions (L*W*H)	[cm]	35.9*20.5*35.1	52*51.2*102 / 52*58.8*164	60*50*150
Weight	[kg]	10	N/A	N/A
Power Supply		AC 100V	AC 220V*1 Phase (300VDC* 2A)	AC 220V 50HZ
Ampere	[Amp]	N/A	N/A	N/A
Recommended capacity (storage tank)	[l]	N/A	N/A	N/A
Electrolysis Type		N/A	N/A	Divided or Undivided Cell
Material of devices		N/A	ABS	Acrylic/ UPVC
Mode of Working		N/A	Continuous	Continuous
Pressure Range Allowable	[bar]	N/A	Max.6	1.5 - 4
Flow Rate of Product	[l/hr]	90 / 180 / 300	84 - 417	80 - 600
Water Working Temperature	[°C]	N/A	N/A	45 - 115
NaCl Consumption	[g/hr]	N/A	N/A	N/A
Types of Products		Only Hypochlorous Acid	Alkaline Water (NaOH), Acidic Water (HOCl)	Hypochlorous Acid, Small Amount of H ₂
ORP	[mV]	N/A	N/A	≤1100
Barrier Between Electrodes		N/A	Ion Exchange Membrane	Membrane or Diaphragm or Single Cell
Available Chlorine Concentration	[ppm]	100 / 50 / 30	N/A	40-200ppm (Adjustable)
pH Range	[pH]	2.7 - 6.5	2 - 10	3.0 - 6.5 (Adjustable)
Electrodes Material (lifespan)		N/A	Bipolar, Carbon	Ruthenium Iridium, Oxide Coating, or Titanium Platinum Anode; Pure Titanium, Cathode
HOCl Production Controller		N/A	Flow Sensor 1EA	N/A
Price	USD	N/A	N/A	8910

Company Name (Brand)		AQUAOX	AQUAOX	Tianno
Product Name		EAW	MOW	Rs 6 Lakhs/8.54 Lakhs/5 Lakhs/4 Lakhs/3 Lakhs/3.3 Lakhs
Dimensions (L*W*H)	[cm]	Various	Various	N/A
Weight	[kg]	Various	Various	N/A
Power Supply		N/A	N/A	N/A
Ampere	[Amp]	60	N/A	N/A
Recommended capacity (storage tank)	[l]	60 - 100	25 - 75	N/A
Electrolysis Type		Divided Cell	Single Cell	Divided Cell
Material of devices		PVC	PVC	N/A
Mode of Working		Continuous	Continuous	Continuous
Pressure Range Allowable	[bar]	Min. 1.8	Min. 1.8	N/A
Flow Rate of Product	[l/hr]	60 - 100	25 - 75	12.5 / 20 - 600 / 20 - 600 / 2 / 10 / 42
Water Working Temperature	[°C]	< 25	< 25	N/A
NaCl Consumption	[g/hr]	N/A	N/A	N/A
Types of Products		Alkaline Water (NaOH), Acidic Water (HOCl)	Only Hypochlorous Acid	Alkaline Water (NaOH), Acidic Water (HOCl)
ORP	[mV]	800	700	N/A
Barrier Between Electrodes		Membrane	N	Nafion Membrane
Available Chlorine Concentration	[ppm]	250 - 575	4500 - 5500	Max. 800 / 500 / 500 / 500 / 100 / 200
pH Range	[pH]	7	9	5.5 / 5.5 / 5.5 - 8.5 / 7.5 / 7.5 / 7
Electrodes Material (lifespan)		Ir-Coated Titanium	Ir-Coated Titanium	MMO Coated Titanium Plate Type Anode
HOCl Production Controller		N/A	N/A	N/A
Price	USD	30,000 and up	30,000 and up	N/A

Company Name (Brand)		Dinol	Customized (Alibaba)	Danolyte
Product Name		DN-H50/H100/H300	Natural HOCl hypochlorous Acidic Water Electrolyzed Generator machine	DJIT 300/DJIT 500/DJIT 1000
Dimensions (L*W*H)	[cm]	65*42*130/ 75*45*130/ 85*50*160	110*65*140	43.18*20.32*66.04/ 73.66*30.48*106.68/ 73.66*30.48*106.68
Weight	[kg]	N/A	275	29/33/35
Power Supply		DC 24 V / 24 V / 36 V	AC 220V 50 Hz	AC110/220 V 50 Hz
Ampere	[Amp]	50 / 100 / 300	N/A	10
Recommended capacity (storage tank)	[l]	25 / 30 / 40	N/A	N/A
Electrolysis Type		N/A	N/A	N/A
Material of devices		N/A	SU304, Stainless Steel 304	N/A
Mode of Working		N/A	N/A	N/A
Pressure Range Allowable	[bar]	1 - 3	N/A	3
Flow Rate of Product	[l/hr]	25 / 30 / 40	100	Acidic Water: 13.5/25/51 Alkaline Water: 2/4/8
Water Working Temperature	[°C]	0 - 40	N/A	5 - 35
NaCl Consumption	[g/hr]	N/A	N/A	N/A
Types of Products		N/A	Only Hypochlorous Acid	Alkaline Water (NaOH), Acidic Water (HOCl)
ORP	[mV]	N/A	> 1100	900 <
Barrier Between Electrodes		N/A	N/A	N/A
Available Chlorine Concentration	[ppm]	50 / 100 / 300	100 - 450	500
pH Range	[pH]	2.7 - 3.5	1.5 - 5.5	6.5 - 7
Electrodes Material (lifespan)		N/A	N/A	N/A
HOCl Production Controller		PLC Automatic Program	N/A	N/A
Price	USD	N/A	25,000 - 31,500	N/A

Company Name (Brand)		Chlorking	GenEon	Chlorking
Product Name		HYPOGEN 2 /5	INT01	CHLOR 2.0 MSM
Dimensions (L*W*H)	[cm]	114*48*142	N/A	N/A
Weight	[kg]	36	N/A	N/A
Power Supply		N/A	AC 110V/240V	AC 120-240V 50/60Hz Single phase
Ampere	[Amp]	N/A	8	15
Recommended capacity (storage tank)	[l]	N/A	N/A	N/A
Electrolysis Type		N/A	Divided Cell	N/A
Material of devices		N/A	Steel Case, Powder Coated	N/A
Mode of Working		N/A	Continuous	Continuous
Pressure Range Allowable	[bar]	1.8 - 3.5	N/A	Max. 3.5
Flow Rate of Product	[l/hr]	23 / 57	180 - 540	4543
Water Working Temperature	[°C]	N/A	N/A	15 - 40
NaCl Consumption	[g/hr]	N/A	N/A	N/A
Types of Products		Only Hypochlorous Acid	Alkaline Water (NaOH), Acidic Water (HOCl)	Only Hypochlorous Acid
ORP	[mV]	N/A	N/A	N/A
Barrier Between Electrodes		N/A	N/A	N/A
Available Chlorine Concentration	[ppm]	> 1000	50 - 198	3500 - 5000
pH Range	[pH]	5.5 - 7 (Adjustable)	5.5 - 11.9	N/A
Electrodes Material (lifespan)		N/A	N/A	N/A
HOCl Production Controller		N/A	N/A	N/A
Price	USD	20125.40	N/A	N/A

Company Name (Brand)		NaOClean	FumaGen	CHEMNIUM
Product Name		DES-8000/5000/4000L	FumaGen 30 LS /48/72/96	HD-40L-HClO/60/100/150/200
Dimensions (L*W*H)	[cm]	65*61*130 / 51*51*120 / 47*40*120	N/A	N/A
Weight	[kg]	60 / 40 / 35	N/A	N/A
Power Supply		AC 110 or 220 60 Hz	N/A	380 VAC 50 Hz
Ampere	[Amp]	N/A	N/A	N/A
Recommended capacity (storage tank)	[l]	100 / 50 / 20	N/A	50 / 80 / 120 / 180 / 250
Electrolysis Type		Single Cell	N/A	N/A
Material of devices		N/A	N/A	N/A
Mode of Working		N/A	N/A	N/A
Pressure Range Allowable	[bar]	N/A	N/A	N/A
Flow Rate of Product	[l/hr]	1200 / 600 / 600	200 / 300 / 400 / 500	40 / 60 / 100 / 150 / 200
Water Working Temperature	[°C]	5 - 30	N/A	N/A
NaCl Consumption	[g/hr]	N/A	90 / 143 / 215 / 260	10 - 1000
Types of Products		Only Hypochlorous Acid	Only Hypochlorous Acid	N/A
ORP	[mV]	N/A	>1000	N/A
Barrier Between Electrodes		N	N/A	N/A
Available Chlorine Concentration	[ppm]	100 - 200	150 / 160 / 180 / 200	90
pH Range	[pH]	7 - 7.5	5.5	N/A
Electrodes Material (lifespan)		(10000 hr)	N/A	N/A
HOCl Production Controller		Soft Touch Panel	N/A	PLC
Price	USD	7200 - 13000	N/A	N/A

Company Name (Brand)		GENOX	KIRKMAYER	KIRKMAYER
Product Name		T00/T05/T10/T15/T20	LAMI Series/AMI Series	BMI Series
Dimensions (L*W*H)	[cm]	50*25*64/50*25*64/ 70*33*84/70*33*84/ 85*46*144	Various	Various
Weight	[kg]	30 / 30.5 / 30.6 / 55 / 55	Various	Various
Power Supply		200 - 240 VAC	230 VAC 50/60 Hz - 380 VAC 50/60 Hz 3phase	230 VAC 50/60 Hz
Ampere	[Amp]	13	30 - 270	4 - 15
Recommended capacity (storage tank)	[l]	N/A	N/A	N/A
Electrolysis Type		N/A	N/A	N/A
Material of devices		N/A	N/A	N/A
Mode of Working		N/A	N/A	N/A
Pressure Range Allowable	[bar]	2.5 - 6.2	2.2	2.2
Flow Rate of Product	[l/hr]	9 - 400	50 - 600	5 - 20
Water Working Temperature	[°C]	5 - 40	5 - 40	5 - 40
NaCl Consumption	[g/hr]	N/A	N/A	2.5 - 5
Types of Products		Only Hypochlorous Acid	Alkaline Water (NaOH), Acidic Water (HOCl)	Alkaline Water (NaOH), Acidic Water (HOCl)
ORP	[mV]	N/A	850 - 950	850 - 950
Barrier Between Electrodes		N/A	N/A	N/A
Available Chlorine Concentration	[ppm]	500	500	500
pH Range	[pH]	6 - 8.5	7 - 13	7 - 12
Electrodes Material (lifespan)		N/A	N/A	N/A
HOCl Production Controller		N/A	PLC	PLC
Price	USD	N/A	N/A	N/A

Company Name (Brand)		Danish Clean Water
Product Name		T25N0040/T25N0080/T25N0120/T25N0250
Dimensions (L*W*H)	[cm]	85*46*149 / 85*46*149 85*46*149 / 85*46*149
Weight	[kg]	160 / 175 / 180 / 185
Power Supply		3 x 400
Ampere	[Amp]	16
Recommended capacity (storage tank)	[l]	N/A
Electrolysis Type		N/A
Material of devices		N/A
Mode of Working		Continuous
Pressure Range Allowable	[bar]	3 - 7
Flow Rate of Product	[l/hr]	40 / 80 / 120 / 250
Water Working Temperature	[°C]	5 - 30
NaCl Consumption	[g/hr]	41 - 83 / 125 - 166 / 291 - 333 / 500 - 625
Types of Products		Alkaline Water (NaOH), Acidic Water (HOCl)
ORP	[mV]	N/A
Barrier Between Electrodes		N/A
Available Chlorine Concentration	[ppm]	500
pH Range	[pH]	N/A
Electrodes Material (lifespan)		N/A
HOCl Production Controller		N/A
Price	USD	N/A

11.3 Appendix C - Sample Letter that Was Sent to Some Companies

1. First message :

Dear Sir / Madame,

I found your contact details during a search on the internet and I hope that you would be able to help me.

I hope you are well and this message finds you in good health.

I'm a final-year chemical engineering undergraduate student at BIHE university and I am working on my final project, _My final project is a technology review of electrolytic production of hypochlorous acid combined with a brief economic review. I have been researching for about 2 months, the properties of this acid, its components, as well as the technologies that produce it.

The methodology of my project is essentially a literature review. I would appreciate it if you could kindly provide me with any of the following information about your company and products :

COMPANY NAME	
WEBSITE	
EMAIL	
TELEPHONE	
CONTACT PERSON	

Techno-economic SPECIFICATIONS	Please specify your most popular model				
	Please specify the units of measurement.				
	Name of Device	...	...	...	...
1. Electrode					
	Material (For example, Iridium-Coated Titanium)				
	Plate or cylindrical				

	Dimensions				
2. Cell					
	Material of Construction for the Housing				
	Flat or Cylindrical				
	Number of Electrodes per Cell				
	Capacity (volume)				
	Dimensions				
	Price				
3. Device					
	Continuous or Batch				
	Membrane or Diaphragm or Single cell				
	Voltage (V)				
	Current (A)				
	Plant or Portable, Industrial or Domestic				
	Dimensions				
	Number of Cells per Device				
	Application (For example, food sanitizer, agriculture, medical, disinfection, etc)				
4. Plant					
	Number of Device				
	Number of Pump				
	Piping for Example				

	pipe, Fitting, etc)				
	System for Water Purification (for Example RO, IX, etc)				
	Salt Addition System				
5. Feed					
	Flow rate				
	Ingredient (For example water, NaCl salt, Vinegar, buffering agent, etc)				
	Conductivity				
	Temperature				
	Pressure				
6. Anolyte					
	Flow rate				
	pH				
	ORP mV				
	FAC ppm				
	Shelf life				
	Price				
7. Catholyte					
	Flow rate				
	pH				
	ORP mV				
	FAC ppm				
	Shelf life				
	Price				
8. Economics					
	Price of Device				
	Estimated Cost of Installation				
	Estimated Cost of Feed				
	Volume of product per Annum				

	Turn over per Annum				
	Number of Employees				

Please feel free to include any additional information or Contact me for anything Further

Looking forward to your response at your earliest convenience,

With much appreciation for your assistance in this matter,

Warm regards

Hamed Hadadzade

Cell Mobile : +98 938 270 6865

Available on WhatsApp and skype

Email : Hamed.Hadadzade@bihe.org

2. Second message :

Dear Sir // Madame,

Further to my email of regarding my request for further information for my final year chemical engineering project entitled “Electrolytic Production of Hypochlorous Acid - A Techno-Economic Review”, a point that has been raised about a Confidentiality and Non-Disclosure Agreement.

This is to confirm that in any case any and all information that is provided would be treated in utmost confidentiality and accorded complete respect and would be used only for the purposes of my final year thesis. Also, that if it helps and you prefer, I am prepared and happy to enter into a Confidentiality and Non-Disclosure Agreement with your company, and in this respect, would be happy, if you can kindly send me a copy of your agreement, which I can sign, scan and return to you by email.

I look forward to your response.

Thank you and please feel free to contact me.

Yours sincerely,

Hamed Hadadzade

Cell Mobile : +98 938 270 6865

Available on WhatsApp and skype

Hamed Haddadzadeh
2020 - 2021

Email : Hamed.Hadadzade@bihe.org

My last email that I sent,

Dear Sir / Madame,

I found your contact details during a search on the internet and I hope that you would be able to help me.

I hope you are well and this message finds you in good health.

I'm a final-year chemical engineering undergraduate student at BIHE university and I am working on my final project, _My final project is a technology review of electrolytic production of hypochlorous acid combined with a brief economic review. I have been researching for about 2 months, the properties of this acid, its components, as well as the technologies that produce it.

The methodology of my project is essentially a literature review. I would appreciate it if you could kindly provide me with any of the following information about your company and products :

Please feel free to include any additional information or Contact me for anything Further

Looking forward to your response at your earliest convenience,

With much appreciation for your assistance in this matter,

Warm regards,

Hamed Hadadzade

Cell Mobile : +98 938 270 6865

Available on WhatsApp and skype

Email : Hamed.Hadadzade@bihe.org

11.4 Appendix D - Responses from Some Companies

1. AQUAOX LLC Company

COMPANY NAME	AQUAOX LLC
WEBSITE	WWW.AQUAOX.COM
EMAIL	INFO@AQUAOX.NET
TELEPHONE	561.427.9495
CONTACT PERSON	MICHEL VAN SCHAIK

Techno-economic SPECIFICATIONS	Please specify your most popular model				
	Please specify the units of measurement.				
		Name of Device	...	...	...
1. Electrode		EAW	MOW		
	Material (For example, Iridium-Coated Titanium)	IR-COATED TITANIUM	IR-COATED TITANIUM		
	Flat or cylindrical	CYLINDRICAL	FLAT		
	Dimensions	VARIOUS	VARIOUS		
2. Cell					
	Material of Construction for the Housing	PVC	PVC		
	Flat or Cylindrical	CYLINDRICAL	FLAT		
	Number of Electrodes per Cell	1 OR MORE	1 OR MORE		
	Capacity (volume)	60—100LPH PER CELL	25-75LPH PER CELL		

	Dimensions				
	Price	NOT FOR SALE	NOT FOR SALE		
3. Device					
	Continuous or Batch	CONTINUOUS	CONTINUOUS		
	Membrane or Diaphragm or Single cell	MEMBRANE	SINGLE		
	Voltage (V)	24-48			
	Current (A)	60			
	Plant or Portable, Industrial or Domestic	PORTABLE COMMERCIAL FACILITIES	INDUSTRIAL		
	Dimensions				
	Number of Cells per Device	1 OR MORE	1 OR MORE		
	Application (For example, food sanitizer, agriculture, medical, disinfection, etc)	HOSPITAL GRADE DISINFECTANT / FACILITIES	WATER TREATMENT / AGRICULTURE / HORTICULTURE		
4. Plant					
	Number of Device	1-10	1-10		
	Number of Pump	2 OR MORE	1 OR MORE		
	Piping for Example pipe, Fitting, etc)	PVC	PVC		
	System for Water Purification (for Example RO, IX, etc)	ION-EXCHANGER	ION-EXCHANGER		
	Salt Addition System	BRINE TANK FROM ION-EXCHANGER	BRINE TANK FROM IONEXCHANGER		
5. Feed					
	Flow rate	60-100LPH	25-75LPH		

	Ingredient (For example water, NaCl salt, Vinegar, buffering agent, etc)	NACL	NACL / KCL		
	Conductivity	3-9mS	30-50mS		
	Temperature	<77F	<77F		
	Pressure	>25psi	>25psi		
6. Anolyte					
	Flow rate	85%	100%		
	pH	7	9		
	ORP mV	800mV	700Mv		
	FAC ppm	250-575ppm	4500-5500ppm		
within 10% of setpoint within 25% of setpoint	Shelf life	90-120 days	90-120 days		
		180-360 days	180-360 days		
	Price	FLEXIBLE	FLEXIBLE		
7. Catholyte					
	Flow rate	15%	N/A		
	pH	11.5	N/A		
	ORP mV	-800mV	N/A		
	FAC ppm	5000ppm	N/A		
	Shelf life	24 months	N/A		
	Price	FLEXIBLE	N/A		
8. Economics					
	Price of Device	\$30,000 and up	\$30,000 and up		
	Estimated Cost of Installation	\$5000	\$5000		
	Estimated Cost of Feed				
	Volume of product per Annum	1,000,000 Gallons lifetime	1,000,000 gallons lifetime		
	Turn over per Annum				
	Number of Employees	1	1		

2. DINOL Environmental Protection Technology Company

COMPANY NAME	Dinol environmental protection technology co.,Ltd.
WEBSITE	www.di-nol.com
EMAIL	dinore@126.com
TELEPHONE	+86 18229098616
CONTACT PERSON	Vera Li

Techno-economic SPECIFICATIONS		Name of Device	...	...
1. Electrode				
	Material (For example, Iridium-Coated Titanium)	Anode: Ruthenium iridium oxide coating, or titanium platinum anode Cathode: 2mm thickness pure titanium electrode		
	Flat or cylindrical	Plate structure		
	Dimensions	95mm*95mm*86mm		
2. Cell				
	Material of Construction for the Housing	Acrylic/UPVC		
	Flat or Cylindrical	Cylindrical		
	Number of Electrodes per Cell	6 units		
	Capacity (volume)			
	Dimensions			
	Price	790 \$ (FOB)		
3. Device				
	Continuous or Batch	Continuous electrolysis		
	Membrane or Diaphragm or Single cell	Any one of them will do		
	Voltage (V)	220V 50HZ		

	Current (A)			
	Plant or Portable, Industrial or Domestic	Plant and Industrial and Domestic		
	Dimensions	600×500×1500mm		
	Number of Cells per Device	1 unit		
	Application (For example, food sanitizer, agriculture, medical, disinfection, etc)	food sanitizer, agriculture, hospital, Skin and mucous membrane disinfection, water treatment, Breeding plant, etc.		
4. Plant				
	Number of Device			
	Number of Pump	2		
	Piping for Example pipe, Fitting, etc)	DN15 (1/2")		
	System for Water Purification (for Example RO, IX, etc)	RO/None		
	Salt Addition System			
5. Feed				
	Flow rate			
	Electrolyte Ingredient (For example water, NaCl salt, Vinegar, buffering agent, etc)	NaCl salt(electrolyzer with membrane) Dilute hydrochloric acid(3%)		
	Conductivity			
	Temperature	45° to 115° F 3° to 46° C		
	Pressure	0.15~0.4MPa		
6. Anolyte				
	Flow rate	80L ~ 600L/H (Liters per hour)		
	pH	3.0-6.5(adjustable)		
	ORP mV	≤1100mv		
	FAC ppm	Chlorine concentration: 40-200ppm(adjustable)		
	Shelf life	1-2 year(electrolyzer)		
	Price			
7. Catholyte				
	Flow rate	The side of the cathode chamber generated a small amount of hydrogen.		
	pH			
	ORP mV			
	FAC ppm			
	Shelf life			
	Price			

8. Economics				
	Price of Device	8910 \$ (FOB)		
	Estimated Cost of Installation	10-15\$		
	Estimated Cost of Feed	2-3\$(1 year)		
	Volume of product per Annum	300-5600 t/year		
	Turn over per Annum	12 million RMB		
	Number of Employees	45		

11.5 Appendix E - Papers That Were Sighted

I read those papers and helps me to understanding but not used for references.

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