Analysis of Energy Consumption in Chlor-Alkali Production by Using Plasma Electrolysis Process

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Abstract

Chlor-alkali is one of the most important processes in chemical industry. In this study, the energy consumption on chlorine gas production by electrolysis plasma is examined. Plasma electrolysis can decrease the energy consumption up to 24 times in single compartment reactor and can reach up to 59 times in double compartment reactor compared to electrolysis process in the same reactor configuration. In reactor with single compartment, high voltage results high current that then cause high-energy consumption. The highest chlorine gas production is at 0.5 M and 300 V that results 4.63 mmol for 15 minutes with 134 kJ/mmol Cl_2 energy consumption. Furthermore, in double compartment reactor, current is lower due to its higher distance between two electrodes that makes the higher resistance. The highest chlorine gas production is at 0.5 M and 700 V that results 11.25 mmol for 15 minutes with 16 kJ/mmol Cl_2. The decrease of the energy can be then optimized to meet the lowest energy consumption. Further development of this study will lead to the more effective process of chlor-alkali industry application.

Key words: Chlor, Energy, Production, Plasma Electrolysis

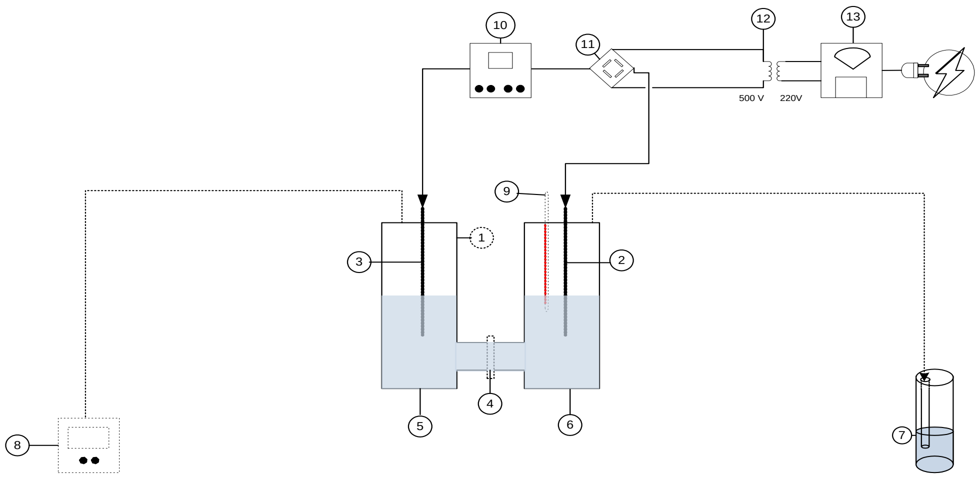
1. INTRODUCTION

The chloralkali process is one of the most important industrial processes producing chlorine and caustic soda that becomes the main feedstock of daily needs products such as medicine, detergent, plastic, deodorants, insecticide, disinfectant, etc. Chlor-Alkali uses the electrolysis process to produce its products (Bommaraju 2011). Electrolysis is a method of compound's bonding separation by passing the electric current. Ionic compound, NaCl, will be decomposed in the solvent and form ions in the solution. Positive discharge electrode is called anode and the negative one is cathode. Each electrode bonds ions that have different discharge, so that ions with negative discharge will go to anode and the positive ions will go to cathode. Nevertheless, electrolysis of NaCl solution (brine electrolysis) used in chlor-alkali production has significant weaknesses, those are low conversion and it consumes much electricity that presents almost 70% of total production cost of the industry (Santorelli 2009). The electricity can't be replaced and substituted by other materials due to its function in electrolysis process. Hence, the intensification of the process is needed to reduce the amount of electricity consumed.

One of the methods that can reduce the energy consumption is plasma electrolysis. The plasma electrolysis process is similar with electrolysis process, but it is done with high enough voltage until the electric spark is formed and producing the plasma in the electrolyte solution.The plasma will produce reactive species such as radicalson large amount which are accelerated by the sharp potential gradient and have enough kinetic energy to induce unique chemical changes in aqueous solutions, so it is able to increase the formation of products in solution several more times than the Faraday electrolysis process and then also reduce the energy consumption (Mizuno 2005, Chaffin 2006).

2. METHOD

The design of reactor is shown in Fig. 1. The reactor has two compartments where one compartment is equipped with graphite as anode and stainless steel as cathode in the other side. This reactor can also be modified as one compartment reactor by closing the connector between two compartments. The reactor is batch system made from acrylic housing filter connected with globe valve. The electric source is connected to 3-kVA-slide regulator with the output is then connected to 4x transformer. Diode Bridge is used to rectify the electric current. The current is measured and noted from ampere-meter Yuhua A830L. The reactor design is also fulfilled with chlorine and hydrogen gas measurement. The chlorine gas produced will be passed into KI 2% solution and hydrogen gas will be passed into hydrogen analyzer. KI will bond the chlorine gas and react to form iodine that results the orange color in KI solution. Then, the solution is titrated by $Na_2S_2O_3$ 0.01 N. This study will analyze the formation of plasma by varying NaCl concentration from 0.05 M to 0.5 M with voltage from 500 V – 700 V. Furthermore, measuring the chlorine gas produced and calculating the energy consumption of the process.



1. Reactor
2. Anode (Graphite)
3. Cathode (Stainless Steel)
4. Connector
5. NaCl Solution (Catholyte)
6. NaCl Solution (Anolite)
7. Bubbler of KI Solution
8. Hydrogen Analyzer
9. Thermometer
10. Ampere-meter
11. Diode “Bridge”
12. Transformer
13. Slide Regulator

Fig. 1. Equipment configuration

3. RESULTS AND DISCUSSION

3.1. Plasma Electrolysis Phenomena

The influence of plasma formation in the electrolysis process can be identified through the current changes that occur. Fig. 2 shows the change in current flow when plasma is formed. At the time of the plasma formed, the current will fluctuate and gradually decline. Plasma electrolysis process begins with the process of electrolysis. Due to the Joule heating, gas bubbles are formed and made vapor sheath on both electrodes (Sengupta 1994, 1997).

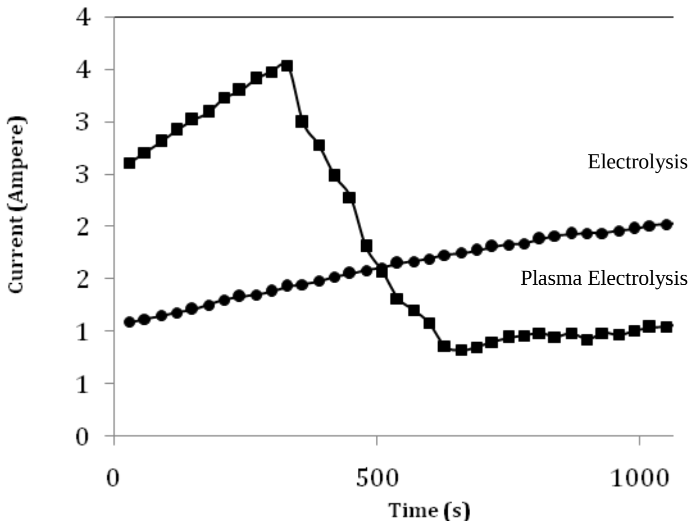


Fig. 2. The current change in 500 V voltages for electrolysis and plasma electrolysis condition of NaCl solution

The formation of gas bubbles will trigger the collision between gas bubbles with an electrical charge so that scattering of energy occurs and let the formation of plasma (Moustakas 2005). Based on the theory of hydrodynamic instability, gas sheath begin to concentrate when the current density reaches the critical value, followed by the reduction in surface tension (Sengupta 1994). The gas sheath makes current flow is reduced due to low conductivity (high resistance) of gas. As a result, when current flows through the gas, electric current are fluctuating and declining.

3.2. Voltage-Current Characteristic

As shown in Fig. 3, plasma in two compartments reactor is formed in voltage above 500 V. The V-I curve has typical characteristic of plasma electrolysis process (Santorelli 2009, Chaffin 2006, Yan 2009). First region is the region where conventional electrolysis occurs (V_A – V_B). This region is shown with the increase of current when the voltage increases. Jin et al (2010) stated that this region is Ohmic region where gas bubbles start to form. Bubbles formation is influenced by hydrodynamic instability of the solution. Based on Helmholtz-Taylor theory about instability, when current density is closed to its critical value, boundary between liquid and gas will be broken which supports the formation of gas sheath (Sengupta 1997). The second area is the region where plasma starts to form which is shown by the decrease of fluctuating current (V_B – V_C). The plasma formed is caused by energy dissipation due to collision of electric charge with saturated gas (Moustakas 2005). Energy dissipation causes temperature increase due to Joule heating effect and gas are ionized and electrons are excited which form the spark of plasma. This region is called as limiting current region or current saturation region. Voltage in B is called as breakdown voltage from all regions. Breakdown voltage is voltage that results the highest current before it fluctuates due to plasma formation.

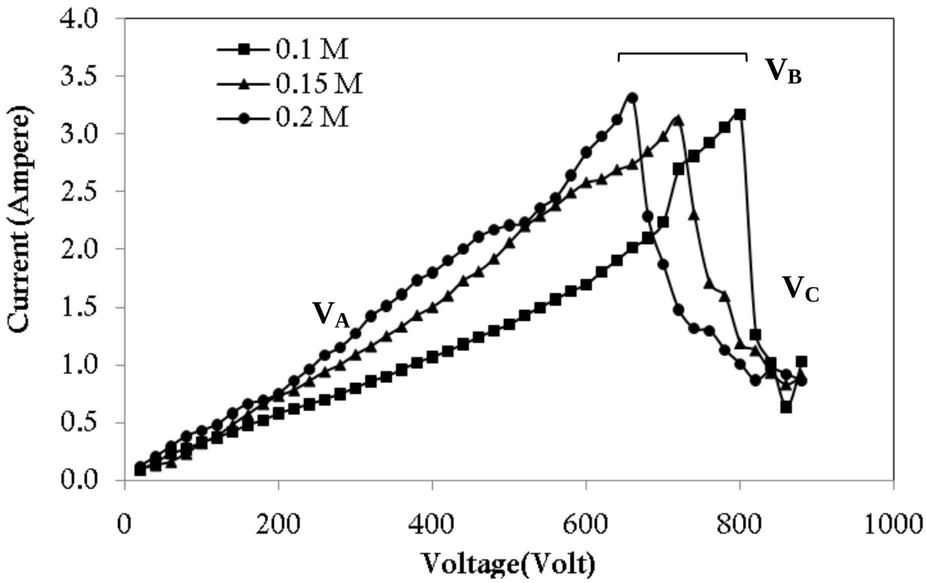


Fig. 3. Current-voltage characteristic curve at 70-80°C in NaCl solution

One of parameters influenced the activity of plasma is the distance between electrodes. Two compartments reactor has about 15 cm in distance between anode and cathode. It will cause the lower current flow due to higher resistance in the solution (Wei 2006). Energy consumption will be lower, however Joule heating effect to the solution will also lower. It makes the formation of gas sheath due to local solvent vaporization around the electrodes need longer time and cause plasma will be more difficult to form. In this study, condition is set in high voltage to make the electric current higher. It will cause to the higher Joule heating, so plasma can be easily formed.

From Fig. 3, the higher the concentration will cause the breakdown voltage lower. It is shown that the higher the conductivity, plasma will be formed in lower voltage. The higher conductivity will cause to the higher current in the same voltage. So, energy dissipation will be higher and make gas sheath formation faster.

3.3. Energy Consumption Analysis

According to energy consumption, plasma electrolysis is lower than electrolysis process (Fig. 4). It is caused by the lower power and may produce more chlorine due to its unconventional radicalization process. Radicals are formed by the excitation of electrons in ionic substances. High energy scattered by the collision inside the solution will cause the electron to be excited. The existence of radicals will increase the amount of chlorine produced because it results faster reaction.

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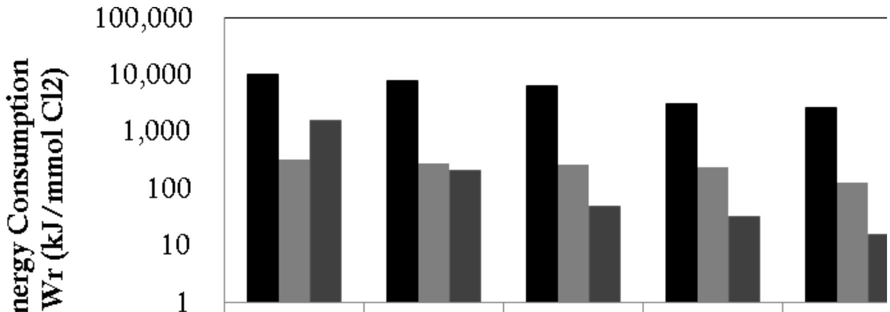

	0.10	0.20	0.30	0.40	0.50
Electrolysis	10,080	7,931	6,238	3,072	2,585
Plasma Electrolysis in Single-Compartment-Reactor	338	292	276	247	134
Plasma Electrolysis in Double-Compartments-Reactor	1,583	211	50	32	16

Fig. 4. Comparison of Energy Consumption per Chlorine Gas Product for 15 Minutes at 70°C – 80°C Temperature

Energy consumption of plasma electrolysis in this study (Fig. 4) can reach 134 kJ/mmol Cl_2 at 0.5 M NaCl solution for single compartment reactor and may reach 16 kJ/mmol $Cl_2$for double compartments reactor. Meanwhile it may reach 2,585 kJ/mmol Cl_2 by electrolysis process in the same condition. This result shows that plasma electrolysis can make the process to be more efficient for about hundred times.

The mechanism of NaCl decomposition into Chlorine gas known until now is by using conventional electrolysis method. In this method, the reaction mechanism happened in the process is as follow (Santorelli 2009):

Reaction in anode

$$2Cl^-_{(aq)} \rightarrow Cl_{2(g)} + 2e^- \quad (1)$$

Reaction in cathode

$$2Na^+_{(aq)} + 2H_2O + 2e^- \rightarrow H_{2(g)} + 2Na^+_{(aq)} + 2OH^-_{(aq)} \quad (2)$$

Total reaction

$$2NaCl_{(s)} + 2H_2O_{(l)} \rightarrow 2NaOH_{(aq)} + Cl_{2(g)} + H_{2(g)} \quad (3)$$

In plasma electrolysis of NaCl solution, Cl- formed will be changed into Chlorine radicals. Two Chlorine radicals will react to each other and form the Chlorine gas compound (Cl_2). Based on the research by Jin et al (2010), the mechanism of species formation of Chlorine active radicals is as follow(Jin 2010):

$$Cl^- \rightarrow Cl\bullet + e^* \tag{4}$$

$$\bullet OH + Cl^- \rightarrow Cl\bullet + OH^- \tag{5}$$

$$Cl\bullet + Cl\bullet \rightarrow Cl_2 \tag{6}$$

$$Cl_2 + H_2O \rightarrow HCl + HClO \tag{7}$$

$$2HClO + H_2O_2 \rightarrow 2Cl^- + O_2 + 2H^+ \tag{8}$$

Besides it produces chlorine gas, there are also reactions that produce side products like hypochlorite acid (HClO). In the mechanism above, HClO formed in the reaction then reacts with H_2O_2 to form H^+ and also $2Cl^-$. The chlorine ions formed then produce the Chlorine gas compound (Cl_2). Hence, it can be said that the mechanism of chlorine compound is done by following two ways of reaction, the reaction of two components of chlorine radical and the reaction of two components of chlorine ions like in the conventional electrolysis mechanism.

4. CONCLUSION

The application of plasma electrolysis can be implemented in the production of chlor-alkali. At the time of the plasma formed, the current will fluctuate and gradually decline. It can reduce the amount of energy consumption because it can run with lower current with the same voltage condition. The plasma electrolysis can result up to hundred times lower of energy consumption compared to electrolysis process. Furthermore, the radicalization process will produce species active that can make the reaction mechanism become unusual. It will lead to the faster gas product formation that then optimizes the overall system of the process.

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