# APPENDIX E

## PUBLICATIONS AND CONFERENCES

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# Mathematical Modeling of Electrical Conductivity in Electrolyte Solution between Two Gas-Evolving Electrodes[1]

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**Abstract**—This paper studies how the electrolyte conductivity has effects on the performance of an alkaline water electrolyzer. A mathematical model of the electrolyte conductivity between two electrodes has been developed based on a combination of electrolyte conductivity, void fraction and velocity of bubble rising in a liquid. The Design of Experiment technique along with statistical method is used to develop the empirical model to investigate the correlation between void fraction, current and solution temperature. The mathematical results show that the drop of the electrical conductivity is caused by an increase of solution temperature and the height of electrode. On the other hand, an increase of bubble diameter results in an increase of conductivity. Subsequently, the mathematical results are compared with the experimental results where the void fraction obtained from the model agrees well with those obtained from the experimental results.

*Keywords*: alkaline water electrolyzer, bubble, conductivity, electrolyte
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## 1. INTRODUCTION

Electrolytic process is gaining importance among the conventional processes of hydrogen production. Its principle lies on the fact that water can be dissolved into hydrogen and oxygen when electricity is charged into the electrodes submerged into an electrolyte. Therefore, it has the advantage of producing extremely pure hydrogen and oxygen and reducing reliance on fossil fuels. The theoretical and experimental research was studied in literature to investigate mass transfer of ions and flow mechanisms of bubble. Attention has drawn to a study of factors that affect the gas production and energy usage. Tangphant et al. [1] studied the ionic resistance occurring between the electrodes at 25°C. It was found that the ionic resistance was increased with the operating time and distance between electrodes. This is consistent with the work reported by Nagai et al. [2] who studied the effect of bubble occurring between electrodes through the void fraction between electrodes. The results showed that an increase of void fraction between electrodes by decreasing the electrode space brought about a decrease of the electrolytic efficiency. Perron et al. [3] developed a mathematical model calculating the total resistance in the form of Laplace's equation and used Finite Element Method (FEM) to analyse the effect of morphology of the bubble layer (position, size and shape of each bubble) on the gas productivity. They found that the relative resistance ($R_t/R_0$) ratio of the total resistance ($R_t$) to the electrolyte resistance in the absence of bubbles ($R_0$) was increased with an increase of bubble diameter. Tangphant et al. [4] also reported that the solution concentration, the distance between electrodes and current density can be correlated with the rate of hydrogen production from the electrolytic reaction to 90.5% of coefficient of $R_2$. In addition, the void fraction also has an effect on buoyancy of the bubble formed during the reaction. Matsushima et al. [5] studied the effect of the bubble under gravity and microgravity and reported that fine gas bubble formed a froth layer in alkaline solution, whereas bubble frequently coalesced in acidic solution. Gas bubble movements were reflected in the coalescence number and bubble resistance time. Golnabi et al. [6] studied the characteristic physical properties of electrical conductivities of pure, distilled, municipal, river and industrial water liquids. It was found that a change in physical properties of the solution would have an effect on the electrical conductivity. The gas bubbles in the electrolyte solution, in the terminal electrodes and within the electrolyzer can cause the resistance of the electrolyte solution which can be changed during the time of gas production. Mat and Aldas [7] and Aldas [8] created mathematical model for the two-phase

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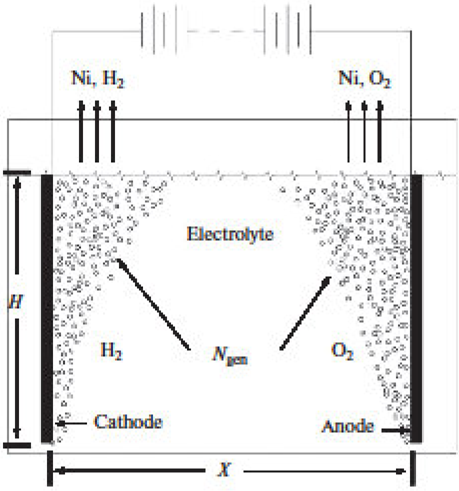

**Fig. 1.** The schematic diagram of the electrolyte solution.

flow in an electrochemical cell. It was found that both current density and bubble size had an effect on the gas release rate which affects the velocity profile in the electrochemical cell. Damme et al. [9] presented the algorithm of bubble nucleation for gas evolving electrodes including bubble growth driven and electrode surface blocking. Caspersen et al. [10] modeled electrolyte conductivity under natural convection and found that the model provides clear tendency for electrolyte conductivity from combinations of current density, pressure and electrolyte width. Aldas et al. [11] studied void fraction distribution and found that the local void fraction was slightly underestimated. Weijs et al. [12] investigated the resistance of the solution and found that the gas voidage in the solution was a function of the distance of the gas-evolving electrode and the absence of gas bubbles in the bulk solution. Sarkar et al. [13] studied and aimed at determining the hydrogen bubble size generated as a function of current density and electrode geometry. It was found that current density had no influence on the detachment diameter and the nucleation rate was increased with increasing current density.

Therefore, this research aims to study the effects of the alkaline electrolytic reaction in the form of electrolyte conductivity via both numerical and empirical models and to compare them with the experimental results. The numerical model gives a relation to the equations of the physical property, while the empirical model is presented with the aim of confirming the numerical results.

## 2. MATHEMATICAL AND EXPERIMENTAL MODELS

Electrolysis is a method of producing hydrogen and oxygen. An alkaline water electrolyzer has been developed in this work due to its low cost and uncomplicated technology. The alkaline water electrolyzer consists of electrodes (anode and cathode), an electrolyte solution, a power supply and a container. Figure 1 shows the schematic diagram of the electrolyte solution. Direct current is applied to electrodes, leading to a flow of electrons from the power supply. The electrochemical reactions for alkaline water electrolysis are shown in Eqs. (R1) and (R2).

$$\text{At anode: } 2OH^- \rightarrow 1/2O_2 + H_2O + 2e \qquad (R1)$$

$$\text{At cathode: } 2H_2O + 2e \rightarrow H_2 + 2OH^- \qquad (R2)$$

$$\text{Net: } H_2O \rightarrow H_2 + 1/2O_2 \qquad (R3)$$

The direct current maintains the electron flow from the negative terminal of the direct current source to the positive terminal at which the electrons are consumed by water to form hydrogen gas and hydroxyl ions. The hydroxyl ions transfer through the electrolyte solution to the anode, at which the hydroxyl ions give away electrons and these electrons return to the positive terminal of the direct current source, producing oxygen gas. Therefore, hydrogen is produced at the cathode and oxygen is produced at the anode and the overall reaction of the alkaline water electrolysis is shown in Eq. (R3) where water is decomposed into hydrogen and oxygen gases. In this section, the mathematical model is developed according to those parameters and compared with the experimental results.

### *2.1. Mathematical Model*

The mathematical model consists of the conductivity model and void fraction model. The parameters affecting the change of the electrolyte conductivity consists of the transfer of charge, current flow in an electrolyte, the void fraction mainly focusing on mixture of electrolyte and gas bubbles and physical parameters relating to the electrolytic process.

**2.1.1. Model assumptions.** To calculate the electrolyte conductivity assumptions are set up as follows:

—The calculation is in one dimension along the electrode height.

—The component of gas phase velocity is calculated by assuming that both hydrogen and oxygen released transform into the gas phase and leave the free surface.

—Mass convection is neglected in this calculation.

—Two electrodes are in parallel; therefore, the ions velocity depend on the electric field strength distribution.

—Current density is constant and along the electrode height.

—Ohmic resistance is low when compared with the reaction resistance.

—The surface area of the electrode is fixed at 100 cm$^2$.

**2.1.2. Model of conductivity.** In the electrolytic process, gas bubble covering the electrode surfaces and ions transferring in the electrolyte are considered as charge transport resistances. The physical model of ohmic resistance is built on the Ohm's law as shown in Eq. (1):

$$R = \frac{L}{\sigma_B A}, \tag{1}$$

where $R$ is the resistance of electrolyte, $L$ is the distance between electrodes, $A$ is the surface area of the electrode. The mixture conductivity ($\sigma_B$) is determined from the void fraction. It is decreased due to the presence of the gas in the electrolyte. The conductivity can be calculated using Bruggeman correction as expressed in Eq. (2):

$$\sigma_B = \sigma_0(1-\alpha_{\text{total}})^{1.5}, \tag{2}$$

where $\sigma_0$ is the conductivity with no bubbles and $\alpha_{\text{total}}$ is the total void fraction.

In addition to the transport of charge, the current flow in an electrolyte is also accompanied by mass transfer. The species mass flux in dilute solution can be calculated using Planck–Nernst law. The conductance of the solution which is the reciprocal of the resistance, is given by Ohm's law. Under electroneutrality state and no current, $I = 0$ is set and $\sigma_0$ can be written as expressed in Eq. (3):

$$\sigma_0 = \frac{F^2|Z_i|^2}{R'T}(C_{i^+}D_{i^+} + C_{i^-}D_{i^-}). \tag{3}$$

**2.1.3. Model of void fraction.** The bubble rise by their terminal speed $\vartheta_i$ refers to the bubbles per unit time leaving and entering the control volume as illustrated in Fig. 2. The number of bubbles has a differential equation in the control volume as described in Eq. (4):

$$\frac{dN}{dt} = (N_{i-1} - N_i)_i\frac{\vartheta_i}{\Delta y} + \dot{N}_{\text{gen},i}. \tag{4}$$

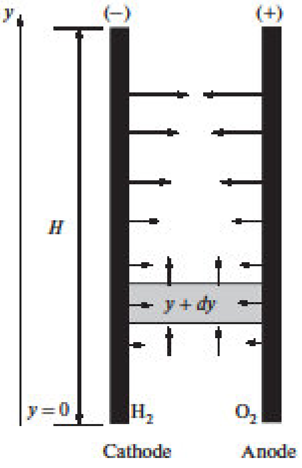

**Fig. 2.** Control volume of the electrochemical cell.

The void fraction of hydrogen and oxygen gas is proportional to the current, diameter of bubble, rising velocity of bubble and geometry of electrode. The volume flux of gas bubble between electrodes is related by the ideal gas law ($V_{\text{gen},i} = \frac{n_i R'T}{P}$) and Faraday's law ($n_i = \frac{Q}{z_i F}$) where $Q = It$ and $Q$ is charge (C), $I$ is current (A), $t$ is time (s) and $T$ is temperature (K). $N_{\text{gen},i}$ can be related to the volume of gas $N_{\text{gen},i} = \frac{V_{\text{gen},i}}{V_{\text{unit}}}$ and $\dot{N}_{\text{gen},i} = \frac{N_{\text{gen},i}}{t}$. Under steady-state condition, $\frac{dN}{dt} = 0$ is assumed. It is noted that the amount of species $i$ entering the control volume is equal to zero ($N_{i-1} = 0$) and by letting $\Delta y \to 0$, Eq. (4) can be written as expressed in Eq. (5):

$$(N_{i,i}) = \left(\frac{\Delta y}{\vartheta_i}\right)(\dot{N}_{\text{gen},i}). \tag{5}$$

The species terminal velocity is a function of bubble diameter ($\vartheta_i = \frac{g d_b^2 \Delta\rho}{18\mu_L}$). The void fraction is equal to the volume of bubble per control volume as

$$\alpha_i = \frac{V_i}{V_{cv}}.$$

The void fraction can be expressed by Eq. (6):

$$\alpha_i = \frac{\phi R'Ty}{Z_i FPX\vartheta_i}. \tag{6}$$

Thus, the average void fraction of all species $i$ equals to

$$\alpha_{av,\text{total}} = \frac{1}{H}\int_0^H \alpha\, dy = \frac{\phi R'TH}{FPX}\left[\frac{1}{Z_{H_2}\vartheta_{H_2}} + \frac{1}{Z_{O_2}\vartheta_{O_2}}\right]. \tag{7}$$

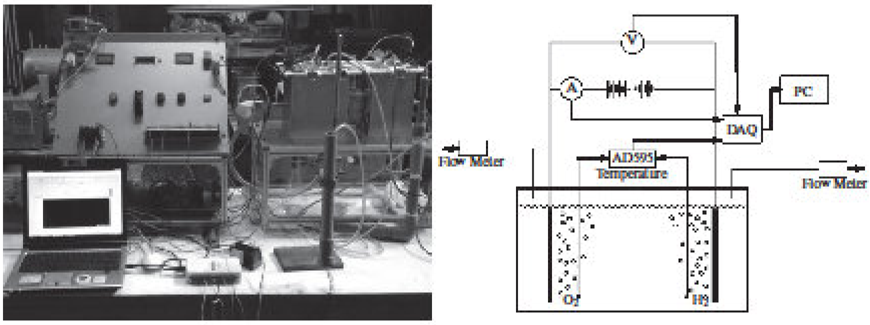

**Fig. 3.** Diagram of experimental apparatus.

Equation (7) enables one to determine analytically the rate of gas bubbles motion with the void fraction.

### 2.2. Experimental Details

The water electrolysis of 20% KOH aqueous solution is conducted under atmospheric pressure using alloy steel as electrodes without a separator as illustrated in Fig. 3. Parameters varied are current, and solution temperature as shown in Table 1. Since it is difficult to directly determine the value of local electrolyte conductivity and void fraction from on-time experiment, the void fraction is compared with the data obtained from gas flow rate measurement. The flow rate multiplied by time is equal to the amount of gas produced. Therefore, Eq. (7) can be compared with Eq. (8):

$$\alpha_{\text{Gas}} = \frac{\text{GasFlowRate} \times \text{Time}}{(\text{GasFlowRate} \times \text{Time}) + V_L}. \tag{8}$$

**Table 1.** Experimental conditions tested

| Factor | Number of level | Value of level |
|---|---|---|
| Current | 3 | 30, 40, 50 A |
| Solution temperature | 4 | 313, 323, 333, 343 K |
| Pressure | | Atmospheric |
| Electrodes | Material | Alloy steel |
| | Distance between electrodes | $X = 20$ cm |
| | Height | $H = 10$ cm |
| | Width | $W = 10$ cm |
| Electrolyte | KOH | 20 wt % |

The response $Y$ is dependent on $k$, for $X_1, X_2, \ldots, X_k$. The relationship between these variables is characterized by a mathematical model called a regression model which presents the results of an experiment. The fitting regression model develops an empirical model relating the amount of current and the electrolyte temperature. The levels adopted for factors are summarized in Table 1. Regression model is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of a problem in which a response of interest is influenced by several variables and a response of interest is then optimized. The form of the relationship between the response ($Y$) and the factors ($X_i$) is given by Eq. (9):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \varepsilon, \tag{9}$$

where $\beta_0$ is the arithmetic mean value of the responses, $\beta_i$ corresponds to the factor effects, and $\varepsilon$ stands for the fitting error. In this study, current and solution temperature are considered as input data and the void fraction as an output ($Y$). It is likely that a model will be a reasonable approximation of the true functional relationship over the entire space of the independent variables.

## 3. RESULTS AND DISCUSSION

The results are divided in two parts: the first part consists of the analysis of experimental data, in particular, the significance of the regression model obtained from the experimental data and the second part focuses on the mathematical model. Table 2 shows the estima-

**Table 2.** Regression model of void fraction fitting characteristics

| Terms | Coefficients | T-score | P-value |
|---|---|---|---|
| Constant | −0.00146 | −5.30 | 0.000 |
| Current | 0.00011048 | 22.98 | 0.000 |
| Solution temperature | 0.00003404 | 9.70 | 0.000 |
|  | $S = 0.000235506$ | R-Sq = 95.0% | R-Sq(adj) = 94.7% |

P-value < 0.05 is significant.

tion of regression coefficients, T-score and P-value between the void fraction and two factors, including current and solution temperature. The linear regression of the measured data shows the best fitting. Factor analysis of current and solution temperature is shown in Eq. (10):

$$\text{Void fraction} = -0.00146 + 0.00011048A + 0.0003404B, \quad (10)$$

where A is the current (A) and B is the solution temperature (K).

Figure 4 shows the experimental results of void fraction obtained from the gas flow rate measurement method compared with the mathematical results. It can be seen that void fraction is increased linearly with an increase of solution temperature due to the rise of solution temperature affecting the reaction rate of the electrolytic process. The experimental data show a good fit over the complete solution temperature range with a relative difference of 2.16% at 313 K and 0.85% at 343 K of 0.3 A/cm$^2$. At 0.5 A/cm$^2$, a relative difference of 2.87% can be found at 313 K and 0.39% at 343 K. It is clearly seen that mathematical model is capable of predicting void fraction in the electrolytic cell.

Figure 5 shows the relationship between the solution temperature and the electrolyte conductivity. Generally, the higher solution temperature causes the increase of bubble volume and the decrease of reversible potential. In the meanwhile, the increase of bubble volume is related to both the direct increase of void fraction and the decrease of driven force of ions in electric filed which results in the increase of void fraction. With the increase of void fraction, the conductivity of the electrolyte can be reduced since the path of charged ion is occupied by gas volume. Thus, the increase of bubble volume leads to the decrease of the conductivity of the electrolyte. In addition, the increase of solution temperature affects the decreasing voltage of the system, resulting in a reduction of ionic conductivity. When considering the effect of current density, it can be found that the electrolyte conductivity of the higher current density is lower than the electrolyte conductivity of the lower current density since, at the higher current density, more amount of bubbles are occurred by the chemical reaction according to Faraday's law. In case the without current applied [14], the electrolyte conductivity is increased with an increase of solution temperature since the bubbles are

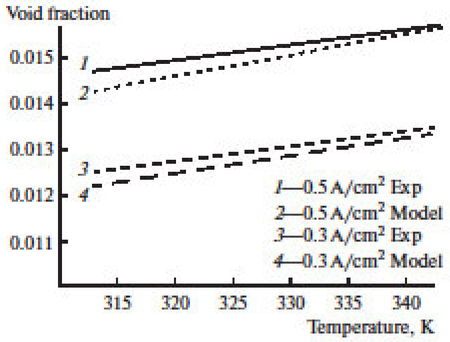

**Fig. 4.** Comparisons between experimental and modeling results.

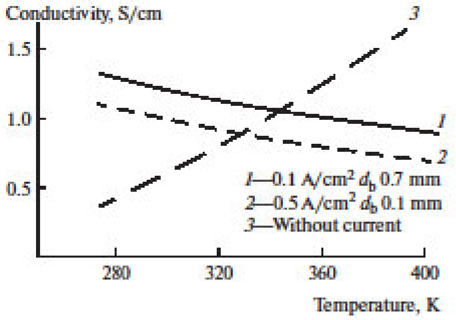

**Fig. 5.** The relationship between the solution temperature and the electrolyte conductivity.

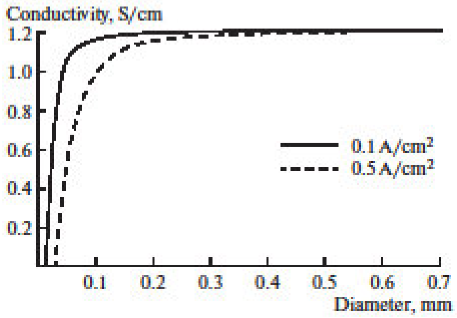

**Fig. 6.** The relationship between the bubble size and the conductivity of the electrolyte.

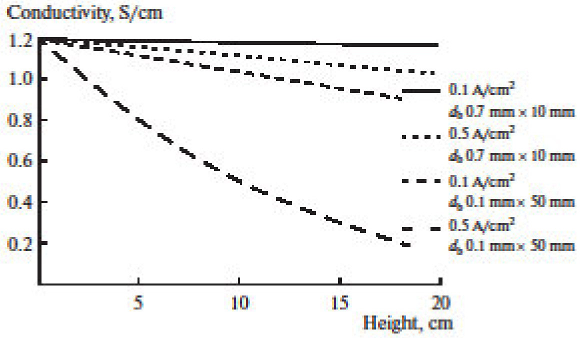

**Fig. 7.** The relationship between the height of the electrodes and the conductivity of the electrolyte.

not presented in the electrolyte. Consequently, the ions in the electrolyte can move more conveniently at the higher kinetic energy with an increase of solution temperature.

Figure 6 shows the relationship between the bubble size and the conductivity of the electrolyte at pressure of 1 atm, solution temperature of 298 K and distance between electrodes of 20 cm. It has been found that the gas bubble in the range of 0.2–0.7 mm in diameter does not affect the conductivity of the electrolyte. However, the diameter of bubble is related to the bubble rising speed. The smaller bubbles would move at slower velocity than the larger ones due to higher frictional force between the liquid and gas phases. Similarly, Sarkar et al. [13] reported that hydrogen produced at the electrode and dissolved directly into the liquid would diffuse in to the rising bubble. Therefore, very small bubbles could cause a change in conductivity than those larger ones. From Fig. 6, it can be seen that, when the current density is increased, the influence of diameter becomes more distinct. It can be implied that the conductivity drop due to gas evolution can be compensated by increasing the diameter of the bubbles. Sarkar et al. [13] also discussed that the current density hardly has influence on the detachment diameter.

Figure 7 shows the relationship between the height of the electrodes and the conductivity of the electrolyte. The surface area of the anode is fixed at 100 cm$^2$ and only the height of the electrode is varied as well as that of the cathode. It can be seen that electrolyte conductivity at lower current density is higher than that of the higher current density at all range of current density because less gases are evolved in the electrolyte. In addition, when the electrode height is increased, the electrolyte conductivity is decreased due to gas bubbles evolve at the electrodes become in-homogeneously polarized as a result of the uneven gas phase distribution along the electrode. This is because the accumulation of gas bubbles is occurred on the electrode and, therefore, blocks the flow electrical current.

## 4. CONCLUSIONS

The mathematical model of electrical conductivity under a convection state is solved by the transport equation for both gaseous and liquid phases. The model results give good agreement with the experimental results. The experiment has been developed to measure void fraction, validate and improve the mathematical model. The void fraction is measured with a system based on gas production rate changes. From the results, it is found that the overall electrolyte conductivity is decreased with an increase of solution temperature and the height of electrodes since the increasing of solution temperature affects the decreasing reversible potential and the height of electrode causes the accumulation of gas bubbles on the electrode. On the other hand, the increase of bubble diameter results in an increase of conductivity. This is because bubble size is related to the frictional force between the liquid and gas phases.

## ACKNOWLEDGMENTS

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# Improving the gas productivity of the alkaline electrolyzer through the circulation technique

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## Abstract

This research aims to study and improve the efficiency of a KOH electrolyzer through the gas productivity of the electrolyzer with different the circulation technique. In this work, the conceptual design of an electrolyzer falls into 2 categories; without pumping and with pumping. Direct current electricity at 5 different levels of 10, 15, 20, 25 and 30 A are charged into the system and the gas flow rate generated from the electrolyzer is subsequently monitored. The results show that at 30 A the gas generated from the circulation with pumping and the circulation without pumping are 2.31 litre/min and 1.76 litre/min, respectively. It is also found that the energy consumed by both techniques is the same; however, the circulation with pumping design shows the better gas productivity than that of the circulation without pumping design.

**Keywords :** Alkaline water electrolysis, Electrolyzer, Energy consumption, Gas production rate

## 1. Introduction

Nowadays, the energy used is very volatile and price sensitive in the marketplace [1, 2]. The reliance on fossil energy alone may result in instability of energy. Hydrogen as an alternative energy can offset fossil energy like solar, wind, hydraulic and wave [3, 4]. Hydrogen can be produced by various processes [1, 3]. The simplest process in the manufacture is the electrolysis process which water splitting has gained importance lately because of its production with neither adverse environmental impact nor fossil fuel requirement. Electrolysis process is a separation of substances from solution by electricity. The electrochemical reactions for alkaline water electrolysis are shown in Eqs.R1 and R2 [1, 5].

At anode: $2OH^- \rightarrow 1/2O_2 + H_2O + 2e^-$ R1

At cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ R2

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Net: $H_2O \rightarrow H_2 + 1/2O_2$ R3

The direct current maintains the electron flow from the negative terminal of the direct current source to the positive terminal at which the electrons are consumed by water to form hydrogen gas and hydroxyl ions. The hydroxyl ions transfer through the electrolyte solution to the anode, at which the hydroxyl ions give away electrons and these electrons return to the positive terminal of the direct current source, producing oxygen gas. Therefore, hydrogen is produced at the cathode and oxygen is produced at the anode and the overall reaction of the alkaline water electrolysis is shown in Eq.R3. The electrolysis process is not widely renowned due to the high cost of energy consumption and efficiency of process [6]. Therefore, an alkaline water electrolyzer is developed in this work due to its low cost and uncomplicated technology. The alkaline water electrolyzer consists of electrodes (anode and cathode), an electrolyte solution, a power supply and a container [1, 7 and 8]. Ohmic resistance is a type of electrical resistance, which can cause a voltage loss according to Ohm's law. The electrolyzer resistance varies with wire and connector resistance, electrodes resistance (anode and cathode), bubble resistance (hydrogen and oxygen bubble) and electrolyte ions resistance. Hydrogen and oxygen gas bubble are formed on electrode surface. The gas bubble covering the electrode surface is assumed as an additional electrical resistance to the system. Therefore, the bubble phenomenon is relevant to parameters such as bubble rise, the space between electrodes and pressure [9-11]. Literature has been devoted to the development of correlation of gas bubble on the electrical resistance of the electrolyte in which Eq. 1 can be used to determine the bubble resistance [1, 12 and 13].

$$R_{bubble,j} = \frac{x_j}{A\rho_{B,j}} \tag{1}$$

The resistance of ionic solution and bubbles can be modeled as a function of time, diameter of bubble, pressure and temperature. $\rho_B$ from Eq. 1 can be related to the electrical conductivity of the electrolyte when bubbles are neglected. According to the Bruggeman equation, $\rho_B$ can be expressed in Eq. 2.

$$\frac{\rho_B}{\rho_0} = (1-\alpha)^{\frac{3}{2}} \tag{2}$$

where, $R_{bubble,j}$ is resistance of the electrolyte of species j, $\rho_0$ is electrical conductivity, $\rho_B$ is mixture conductivity, $x_j$ is distance between electrodes of species i, $A$ is area and $\alpha$ is void fraction. The characteristic physical properties of electrical conductivities of pure, distilled, municipal, river and industrial water liquids. It was found that a change in physical properties of the solution would have an effect on the electrical conductivity [12]. The gas bubbles in the electrolyte solution, in the terminal electrodes and within the electrolyzer can cause the resistance of the electrolyte solution which can be changed during the time of gas production.

In order to improve the efficiency of the electrolysis process, factors affecting the process must be aware of. Factor affecting the efficiency of electrolysis is the resistance that occurs in electrolyte including the ionic and bubble resistance as aforementioned. The improvement or the change in physical properties of the solution would have an effect on the electrical conductivity. The objective of work is to improve the electrolyte conductivity by means of circulation by pumping the electrolyte solution and to study the amount of gas generated. The effect of circulation with pumping and circulation without pumping on the gas production will be investigated and the results will be subsequently discussed.

## 2. Experimental apparatus and method

The water electrolysis of KOH solution is conducted under atmospheric pressure using alloy steel as electrodes. Each side of electrode is 400 mm$^2$. The concentration of electrolyte is 10 %wt and 95% purity. Parameters varied are current, without pumping and with pumping as shown in Table 1. The diagram of the experimental apparatus is shown in Fig.1. The liquid container (250 mm long x 150 mm wide x 250 mm high) is made of polymethyl methacrylate, in which the electrodes are completely immersed with a certain space.

AC power supply is connected to a bridge rectifier through a step down transformer (5.3 KVA, input: 220/230 V AC). The electrodes are connected with AC to DC converter. Regulated DC power supply working in the range of 10-160 A is used and the current is adjusted in the range of 10-30 A. Voltmeter (V) and ammeter (A) are connected in parallel and series respectively to the electrolyzer to measure voltage and current applied to electrolytic process. The gases obtained from the cathode and the anode is collected separately in gas tube and the volume of gas produced is measured with GAS Mass Flow Meter and re-checked by water displacement. Temperature, voltage and current are recorded by the NI-USB6218 (DAQ).

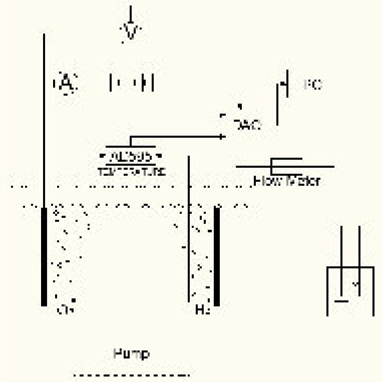

Figure 1 Diagram of experimental apparatus.

In this study, current and electrolyzer are considered as input data and the gas production rate as an output (Y). The levels adopted for factors are summarized in Table 1. There is also a study the effect of electrolyte circulation by pumping. However, the study did not focus on the amount of oxygen existing in the electrolyte solution.

| Factor | Number of Level | Value of Level |
|---|---|---|
| current | 5 | 10, 15, 20,25, 30 (A) |
| circulation technique | 2 | the circulation without pumping and<br>the circulation with pumping |
| Pressure |  | Atmospheric |
| Electrodes | Material | alloy steel |
| Electrolyte | KOH | 10% wt 95% purity |

Table 1
Parameters of Experimental.

## 3. Results and discussion

In the tests, an electrolyzer cell was designed and tested at temperature between 40 °c and 70 °c and at atmospheric pressure. The experimental results of the factors affecting the gas production rate are shown in Figs. 2 and 3. The difference between the gas production rate of circulation without pumping and the gas production rate of circulation with pumping are shown in Fig.2. As can be seen, the gas production rates vary from 0.86 litre/min at 10 A to 1.76 litre/min at 30 A when the electrolyzer is used by circulation without pumping, while the gas production rates are much higher in case of circulation with pumping, varying from 0.92 litre/min at 10 A to 2.31 litre/min at 30 A. In fact, the difference of gas production rate is caused by the conductivity of electrolyte solution. In case of circulation without pumping, the conductivity was not consistent since the gas bubble occurs at the electrode surface. As a result, the electrical resistance of the electrolyte solution is higher and the conductivity of the electrolyte is decreased. In case of circulation with pumping, the bubble is dispersed throughout the electrolyte in which the bubbles layer thickness on the electrode surface is decreased, so the conductivity of the electrolyte is increased significantly especially at higher current.

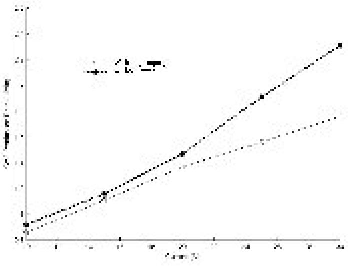

Figure 2 Current - gas production rate comparison of various circulation techniques.

Fig. 3 also shows the gas production rate as different power consumption of the electrolyzer operating with the circulation without pumping and the circulation with pumping. It can be noted that the gas production rate range from 0.92 litre/min at 106 watt (10 A) to 2.32 litre/min at 520 watt (30 A) of circulation with pumping and, in case of circulation without pumping, the gas production rate ranges from 0.86 litre/min at 112 watt (10 A) to 1.76 litre/min at 408 watt (30 A). These results express that, at the same power, the circulation with pumping produces gas volume higher than that of the circulation without pumping.

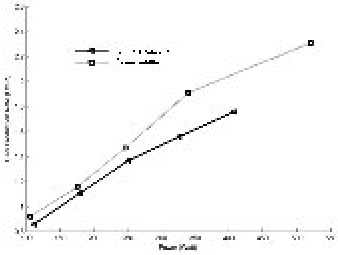

Figure 3 Power consumption - gas production rate comparison of various circulation techniques.

From Figs.2 and 3, the gas production rate is proportion to the amount of the current (electrons) applied. In addition, when the current is increased, the gas production rate of circulation without pumping is lower than the gas production rate of circulation with pumping because the accumulation of gas bubble is occurred on the electrode surface and, therefore, blocks the flow of electrical current. Sarkar et al. [14] reported that gas produced at the electrode and dissolved directly into the liquid would diffuse in to the rising bubble. Therefore, the bubbles layer could cause a change in conductivity than those larger ones.

## 4. Conclusions

In this paper, the electrolyzer performance was tested using terminal current measurements involving current of up to 30 A, while different the circulation techniques are compared to improve the efficiency of the electrolysis process. Gas bubble is formed and covers the electrode surface which is assumed as an additional electrical resistance to the system, leading to the low efficiency of the electrolysis process. The physical properties of the electrolyte related conductivity such as bubble layer at electrodes surface can be reduced by improving mass transport which is consisted in the electrical conductivity of the electrolyte. The results show that at 30 A the gas generated from the circulation with pumping and the circulation without pumping are 2.31 litre/min and 1.76 litre/min, respectively. Therefore, in the development and improvement of electrolyzers, it is important to understand the behavior of these factors in order to minimize the bubble effect which holds a key to the electrolyzer efficiency improvement.

## 5. Acknowledgements

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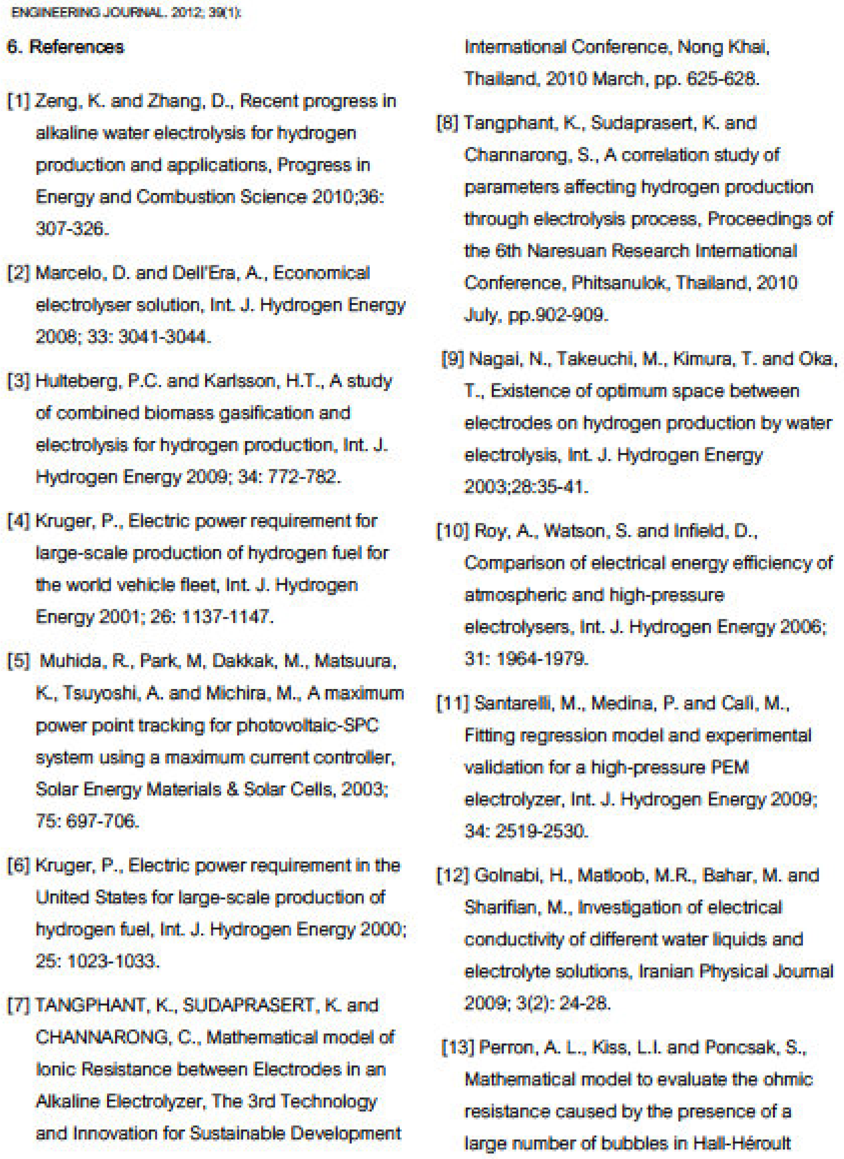

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# Mathematical Model of Ionic Resistance Between Electrodes in an Alkaline Electrolyzer

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## Abstract

This paper proposes an ionic resistance model in order to evaluate the resistance of solution with mass diffusion of concentration depending on time and distance between electrodes in an alkaline electrolyzer. The electrode surface is under the room temperature of 25 °C. An initial concentration of KOH solution is equal to 7.64 $molL^{-1}$ and an electrode surface area is 100 $cm^2$. It is found that the solution resistance is raised up as time and the distance between electrodes are increased. This results in an increase of ohmic loss at the electrolyte.

**Keywords:** Concentration of solution / Ohmic Drop / Resistance of Electrolyte, Electrolyzer

## 1. Introduction

Electrolysis is an alternate method of producing hydrogen. It is well known for its independence of fossil fuel as well as its simple operation. Water contained in an electrolyzer is separated into hydrogen on the cathode side and oxygen on the anode side by applying the power source. The electrolyzer consists of electrodes (anode and cathode), an electrolyte solution, a separator and a container. There are several types of electrolyzers available and alkaline electrolyzer is one of the well known types using NaOH or KOH solution as an electrolyte. The electrochemical reactions for alkaline water electrolysis are as follows: [1-4]

Anode: $2OH^-_{(aq)} = 1/2O_{2(g)} + H_2O_{(l)} + 2e^-$
Cathode: $2H_2O_{(l)} + 2e^- = H_{2(g)} + 2OH^-_{(aq)}$
Net reaction: $H_2O_{(l)} = 1/2O_{2(g)} + H_{2(g)}$

In the electrochemical system, moving charges between electrodes and the electrolyte are two major types of charged species: electrons and ions. In most electrolyzers, due to its larger size, ion charge transport is far more difficult than electron charge transport, thereby resulting in the resistance to charge transport as a voltage loss. Because this voltage loss obeys Ohm's law, it is called an "ohmic", or "IR loss". Ohmic loss consists of resistance of electrodes ($R_{elec}$) and resistance of ionic ($R_{ionic}$) (electrolyte). [1,5]

The objective of this work is to study the mechanism of ionic resistance in the electrolyte solution. Mathematical model has been developed in order to build the relationship between ionic resistance, distance between electrodes and charging time.

## 2. Theory and Model

Figure 1 shows the schematic diagram of the molar conductivity of the electrolyte. The mathematical model of ionic resistance with material balance has established based on the following assumptions:

1. The mass diffusion in y and z directions is neglected.
2. The concentration of the diffusing substance depends on the time and the coordination.
3. Physical properties are

$F = 96548 (Cmol^{-1})$

$R = 8.314 (Jmol^{-1}K^{-1})$

Temperature = 25°C

$u_{K^+} = 7.62x10^{-4} (cm^2V^{-1}S^{-1})$

$u_{OH^-} = 2.05x10^{-3} (cm^2V^{-1}S^{-1})$

$Z_{K^+} = 1$

$Z_{OH^-} = 1$

4. The models of mass migration, convection and membrane are neglected.

The resistance of the electrolyte conductor is dependent on the conductor's geometry and conductivity. The form of resistance can be shown in Eq.1 in which resistance is proportional to area, length and conductivity. [1,4,5]

$$R_{ionic} = \frac{L}{\sigma A} \qquad (1)$$

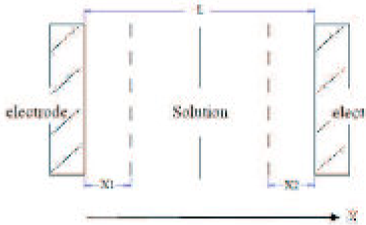

Fig .1 Diagram of molar conductivity of the electrolyte

where $R_{ionic}$ is the resistance of ionic, L is the length, A is the area of electrode and σ is the conductivity of solution.

Electrolyte conductivity (σ) which permits the flow of charge is driven by an electric field. The electrolyte's conductivity is influenced by 2 parameters: a number of transport charge and the mobility of electrolyte. Electrolyte conductivity can be defined by Eq.2 as [5]

$$\sigma_i = (|Z_i|F)c_i u_i \tag{2}$$

where $Z_i$ is the charge number, F is the Faraday's constant, $c_i$ is the concentration of species j and $u_i$ is carrier mobility.

**2.1 Diffusion in electrolyte solution**

For the simple case of a none-conducting electrolyte, the diffusion is dependent on the concentration of the diffusing substance, time and coordinates in the form of partial differential equations as shown in Eqs.3 and 4. [3,6-9]

$$\frac{\partial C}{\partial t} = D\nabla^2 C \tag{3}$$

where C is the concentration, t is the time and D is the diffusion coefficient.

The concentration is a function of coordinates (x) and time (t). The initial condition is thus

$$x > 0\,,\ t = 0\,,\ C = C^0 \tag{4}$$

And the boundary conditions are

$$\begin{aligned} &x = 0\ \ ,\ t > 0\,,\ C = 0 \\ &x \to L\,,\ t = 0\,,\ C = C^0 \end{aligned} \tag{5}$$

Solution of the differential equation 3 together with the initial and boundary conditions yields the relationship [6-9]

$$C(x,t) = C^0 \operatorname{erf}\left[\frac{x}{2D^{\frac{1}{2}}t^{\frac{1}{2}}}\right] \tag{6}$$

where the error function y is defined by Eq.7 and C(x,t) is the concentration of species at distance x at time t. [6,8]

$$\operatorname{erf}[y] = \frac{2}{\sqrt{\pi}}\int_0^y e^{-z^2}dz \tag{7}$$

The diffusion coefficient (D) in Eqs. 3 and 6 is linked to the mobility of species j by the Einstein-Smoluchowski equation: [9]

$$D_j = \frac{u_j RT}{|Z_j|F} \tag{8}$$

where $u_j$ is the mobility of species j, R is gas constant, T is the temperature.

**2.2 Mathematical model**

The resistance of ionic solution can be modeled as a function of distance and time by deriving Eqs. 1 – 8 and expressed in Eq.9:

$$R_{ionic,j}(x,t) = \frac{L}{A \times (|Z_i|F)u_i C_i(x,t)} \tag{9}$$

where

$$\begin{aligned} C_i(x,t) &= C^0 - \int_0^T D_i \frac{\partial^2 C_i(x,t)}{\partial x^2}dt \\ &= C^0 - \int_0^T [D \times \frac{\partial^2}{\partial x^2}(\frac{2C^0}{\sqrt{\pi}} \int_0^{(\frac{x}{2(D^{1/2})(t^{1/2})})} e^{-z^2}dz)]dt \\ &= C^0 - \frac{C^0 x^2(\sqrt{\frac{x^2}{D}}\sqrt{D} \times \operatorname{erf}(\frac{1}{2}\frac{x}{\sqrt{T}\sqrt{D}}) - x}{\sqrt{\frac{x^6}{D^3}}D^{3/2}} \end{aligned} \tag{10}$$

## 3. Results and discussion

The model is employed to study the distribution of the concentration and conductivity of solution for ionic resistance in an alkaline water electrolysis.

**3.1 Distributions of concentration of ions in solution**

Figures 2 and 3 show the distribution of ion concentration of $K^+$ and $OH^-$ at electrode surface, respectively. At electrodes surface where x = 0 cm., the solvent concentration is zero and increased with the distance. The maximum value of the solution concentration is equal to an initial concentration. Having compared figure 2 to figure 3, it as been found that at the same time the value of the solution concentration is not equal due to the fact that the ion diffusion coefficient value is based on the mobility of ion ($u_i$) as expressed in Eq.8.

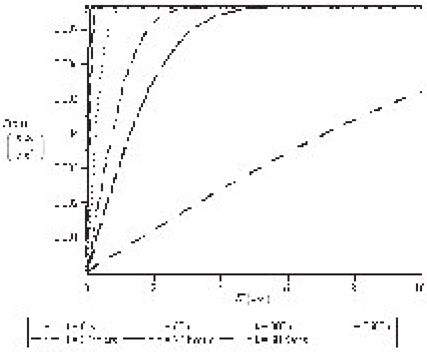

Fig.2 Concentration of $K^+$ at surface electrode

From figures 2 and 3, when operating with the longer period of time, the concentration gradient will be taken placed in the solution. The concentration layer thickness will vary depending on time of use. Initially, the concentration value of $K^+$ is the same as that of $OH^-$ in the reaction. However, it is found that the concentration of $K^+$ is greater than the concertration of $OH^-$, meaning that the concentration gradient layer thickess of $K^+$ is less than that of $OH^-$.

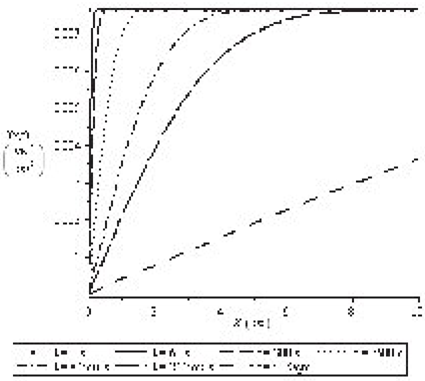

Fig.3 Concentration of $OH^-$

### 3.2 Distributions of conductivity of ions in solution

The graph relationship between conductivity and distance as expressed in Eq.2 can be plotted in figures 4 and 5. Figure 4 shows the conductivity of $K^+$ and $OH^-$. The conductivity of $OH^-$ (1.511 $\Omega$ cm$^{-1}$) is more than the conductivity of $K^+$ (0.562 $\Omega$ cm$^{-1}$). This is due to the influence of the higher mobility of $OH^-$ resulting the higher concentration as shown in figures 2 and 3, respectively.

Figure 5 represents the total value of the electrolyte conductivity of the two ion species ($K^+$ and $OH^-$). Electrical conductivity values in the solution at starting time (t = 0) is equal to 2.073 $\Omega$ cm$^{-1}$. Up until 8 hours, electrical conductivity of solution at electrode surface (distance (X) = 0 cm.) is equal to zero. An increase of the distance from the electrode surface raises the solution conductivity abruptly until it reaches 2.073 $\Omega$cm$^{-1}$ at 5 cm. Subsequently, the conductivity is equal to an initial value at 2.073 $\Omega$ cm$^{-1}$. For the time up to 24 hours, electrical conductivity behaves similarly. The electrolytes solution, conductivity increases with an increase of the distance until it reaches 9 cm. approximately.

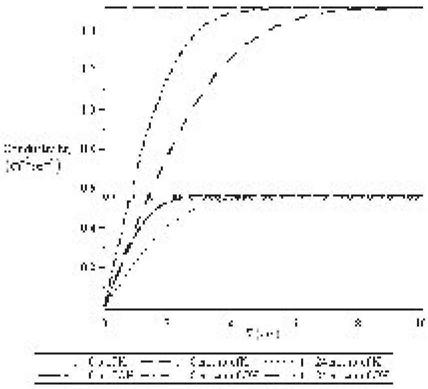

Fig. 4 Conductivity of $K^+$ and $OH^-$

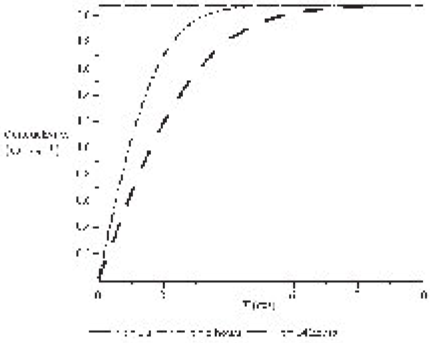

Fig. 5 Conductivity of KOH solution

### 3.3 Distributions of resistance of solution

From Eq. 1, the surface area is 100 cm$^2$, length (L) is in the range 0 – 10 cm, the temperature is 25°C and the conductivity of solution is derived from Eq.2.

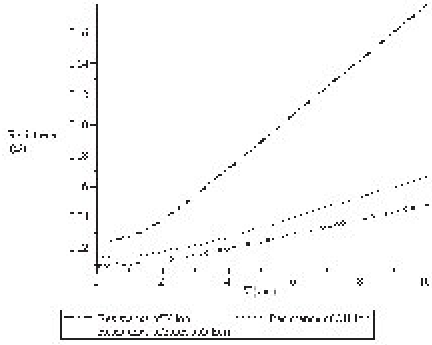

Fig. 6 Ionic resistance over time up to 8 hours

The relationship between the electrolyte resistance and the distance between electrode surface is shown in figure 6. It can be seen that the resistance of solution of $K^+$ is higher than that of solution of $OH^-$. When the two ion species combine together, the total resistance is decreased since the two ions help to mediate current. It is also the relationship between the resistance and the distance found that is non-linear in the range of 0 – 3 cm because the solution concentration close to the electrode surface form the concentration gradient. Apart from 0-3 cm, between 3 – 10 cm, the linear relationship is found due to a constant solution concentration. As a result, the resistance depends on the length or distance between of electrodes.

## 4. Conclusions

This work has analyzed the behavior of a solution resistance at room temperature, without migration and convection. As it is expected, resistance of solution is dependent on time and positions electrodes. In particular, the conductivity of solution related to the time, distance and diffusion coefficient of ions. As the time is increased, a reduction of the electrolyte conductivity is occurred, leading to an enhance of the electrolyte resistance and subsequently, the higher ohmic loss. Apart from the time of operation, it is also found that the solution resistance increases as the distance between electrodes increases.

## Acknowledgments

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# A Correlation Study of Parameters Affecting Hydrogen Production Through Electrolysis Process

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## Abstract

This research aims to investigate the correlation between hydrogen production rate and other three factors: solution concentration, current density and distance between electrodes. The results unveil that the hydrogen production rate depends on two parameters, which are the current density and concentration of the solution, respectively. Efficiency is inversely proportional to the hydrogen production rate. By consuming 384 Watt of electricity, the hydrogen production rate reaches its highest with the efficiency of 15.35%. However, when hydrogen production efficiency of the system is 23.88%, 81.55 Watt of electricity is consumed.

**Keywords:** Alkaline Electrolyzer , Efficiency , Electrolysis , Hydrogen Production Rate

## Introduction

Hydrogen production by electrolytic water splitting has gained importance lately because of its production with neither adverse environmental impact nor fossil fuel requirement. Electrolysis process is a separation of substances from solution by electricity. For an alkaline water electrolyzer, it consists of electrodes (anode and cathode), an electrolyte solution, an electrolyte voltage, a separator and a container. On the anode side, water is dissociated to produce gaseous oxygen. On the cathode side, hydrogen ions ($H^+$) combine with electrons to form gaseous hydrogen. The electrochemical reactions for the alkaline water electrolysis are as follows: (Casper, 1978; Grimes et al., 2008; Oldham & Myland, 1994; Rieger, 1994)

Anode: $H_2O = 1/2O_2 + 2H^+ + 2e^-$
Cathode: $2H^+ + 2e^- = H_2$
Net reaction: $H_2O = 1/2O_2 + H_2$

From the literature reviews, it has been observed that several parameters have effects on the hydrogen production rate. Factors involved in this hydrogen production process include types of solution, pH, current density (Dieguez et al., 2008; Kilic et al., 2008; Ursua et al., 2009), distance between electrodes, types of electrode material (Zhigang et al., 1999), solution concentration (Boll et al., 2003), pressure, temperature (Biaku et al., 2008; Grigoriev et al., 2009; Roy et al., 2006; Santarelli et al., 2009), types of power supply (Dieguez et al., 2008; Ursua et al., 2009) and solution flow rate (Kilic et al., 2008; Marangio et al., 2009). Alkaline electrolyzer is one type of electrolyzers using a solution of high pH values such as NaOH or KOH solution. Alkaline electrolyzer is used under low temperature condition (less than 150 °C) to produce hydrogen with the purity of 99.8% or to produce gas at rates from 10 to 100 $m^3h^{-1}$. Ursua et al. (2009) studied the nature of electric power supply. It has been found that by supplying a half phase, energy loss is occurred, higher than that of a full-bridge. The hydrogen production rate is proportional to the electricity supply. Boll et al. (2003) conducted a research on electrolyzer at high temperature and pressure. At high temperature, potential was decreased while the higher pressure resulted in higher potential power. Dieguez et al. (2008) worked on the thermal performance of the alkaline electrolyzer. In a study, two types of power supply (EPS and IGBT-based electronic converter (EC)) were used and it was found that the temperature of the electrolyzer was increased rapidly when the power supply EPS was used as a result of the circuit arrangement in the device. Mathematical model described the energy equation of electrolyzer was preferred in terms of the heat capacity of the electrolyzer which was $174 kJ^{\circ}C^{-1}$ while the heat losses was approximately $4.3\ W(m^{2\circ}C)^{-1}$ and thermal resistance was $0.164\ ^{\circ}CW^{-1}$. Ulleberg (2003) developed a mathematical model of alkaline electrolyzer. This model has evolved the theory thermodynamic systems, heat transfer and chemical relationships of power that can integrate into the solar cell system. As a result, the production of hydrogen by electrolysis process yielded hydrogen and oxygen production rate with high purity. It was noted that using sources from electrical power generation from renewable energy cause hydrogen production system with a truly clean energy.

From previous relevant research, it can be seen that there are factors affecting the hydrogen production in the electrolysis process, such as temperature, pressure, concentration, current density, type of electrodes, flow rate of solution, etc. Therefore, in this research, some factors affecting the incidence of hydrogen production are studied and used as guidelines in developing electrolyzers. This research aims to conduct the correlation study of factors related to the hydrogen production rate by the alkaline electrolysis process using design of experiment (DOE) and statistic method. The effects of solution concentration, current density and distance between electrodes on the hydrogen production will be investigated and the results will be subsequently discussed.

**Experimental apparatus and method**

The water electrolysis of NaOH aqueous solution is conducted under atmospheric pressure using alloy steel (stainless steel) as electrodes. Each side of electrode is $336\ mm^2$. Parameters varied are current density, distance between electrodes and solution concentration without a separator as shown in Table 1.

Table 1 Levels of the factors.

| Factor | Number of Level | Value of Level |
|---|---|---|
| concentration | 5 | 0.1, 0.5, 1.0,1.5, 2.0 ($molL^{-1}$) |
| current | 5 | 5, 10, 20,30, 40 (A) |
| distance of electrode | 3 | 55, 100, 145 (mm.) |

In this study, current density, distance between electrodes and solution concentration are considered as input data and the hydrogen production rate as an output (Y). The levels adopted for factors are summarized in Table 1. Response surface methodology or RSM is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of a problem in which a response of interest is influenced by several variables and the objective is to optimize this response. The form of the relationship between the response (Y) and the factors ($x_i$) is given by Eq.1 which is called the second-order model. It is used for a polynomial of higher degree (Montgomery, 2001).

$$Y=\beta_0+\sum_{i=1}^{k}\beta_i x_i+\sum_{i=1}^{k}\beta_{ii}x_i^2+\sum_{i<j}\sum\beta_{ij}x_i x_j+\varepsilon \qquad (1)$$

where $\beta_0$ is the arithmetic mean value of the responses, $\beta_i$ corresponds to the factor effects, $\beta_{ii}$ is the quadratic effects and $\beta_{ij}$ is the interactions between the various factors. The $\varepsilon$ variable stands for the fitting error.

Almost all RSM problems use one or both of these models. Of course, it is likely that a polynomial model will be a reasonable approximation of the true functional relationship over the entire space of the independent variables.

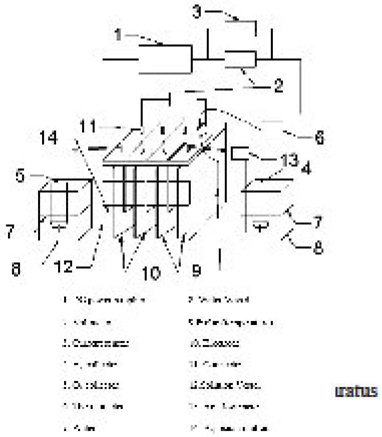


Fig.1 shows the diagram of the experimental apparatus. The liquid container (200 mm long x 150 mm wide x 150 mm high) is made of methyl methacrylate, in which the electrodes are completely immersed and fixed in parallel with a certain space. DC power supplier enables DC current up to 40 A between electrodes generating current density in a range of 0.015 to 0.12 Amm$^{-1}$. Both hydrogen and oxygen gases generated are collected in $H_2$ and $O_2$ collector bottles through water. The temperature of the aqueous solution is measured by thermometer. The surface of electrodes is polished after each experiment.

The efficiency of hydrogen production is qualitatively evaluated and compared by energy consumption at a certain current and voltage. The voltage between electrodes is measured by a voltmeter, while DC current is measured by a current sensor.

## Results and discussion

In the tests, alkaline water electrolyzer is used. Taking into account the number of factors and levels, the full factorial design includes 5 x 5 x3 x 3 = 225 experiments.

The experimental results of the main factors affecting the hydrogen production rate are shown in Fig. 2. In Fig. 2, the mean hydrogen production rate on y axis is plotted against the current density, distance between electrode and concentration on x axis. It has been found that the change of NaOH concentration affects the incidence of hydrogen. The concentration of 0.1, 0.5, 1.0, 1.5 and 2.0 molL$^{-1}$ correspond to the production rate of approximately 0.185, 0.285, 0.328, 0.335, 0.342 $Lmin^{-1}$, respectively. The hydrogen production rate increases gradually and approaches to a constant value at the higher concentration due to saturation of the solution. By considering the current density, from Fig. 2, it can be seen that current density increases with the hydrogen production rate. Theoretically, it is because the larger amounts of electrons enter to the system, thus higher amount of gas is produced. When the effect of distance between electrodes is considered, it can be found that the hydrogen production rate is increased with an increase of distance between electrodes. This is because the voltage source is trying to maintain levels of electricity to a constant value. Consequently, more energy is added to the system, leading to the higher hydrogen production rate. However, the results of statistical calculations showed that the significant changes of distance between electrodes give insignificant values of the hydrogen production rate as shown in Fig.3 (line3) with significant level at 0.05. The results agree well with the work done by Tangphant et al.(2010) who found that distance between electrodes varies with the electrolyte resistance. The shorter distance between electrodes resulted in smaller resistance, thereby leading to the higher conductivity of the solution. As a consequence, this can be used to improve the design of the electrolyzer and to maintain the electrolyte with the high conductivity.

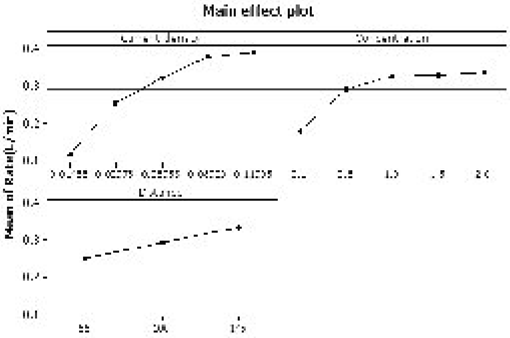


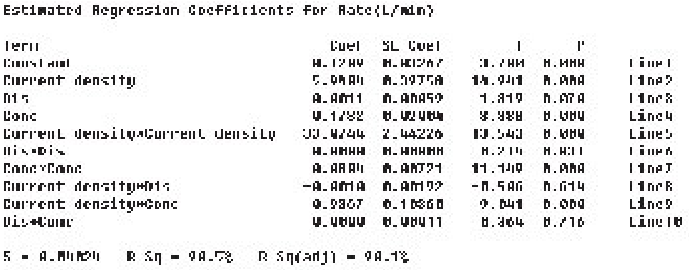
Fig. 2 Effect of current density, solution concentration and distance between electrodes on hydrogen production rate

Fig. 3 shows the estimation of regression coefficients, T-score and P-value between the hydrogen production rate, and three important factors, including current density, concentration, distance between electrodes and others. The coefficient of factors taken into consideration is determined by the P-value which is less than the significance level of 0.05. Factors analysis of current density and concentration without the distance between electrodes are shown in Fig. 4.

Effect of current density and solution concentration on hydrogen production rate are shown in Eq. 2.

$$Y = 0.1821A + 5.8435B - 0.0804A^2 - 33.0744B^2 + 0.9367AB \quad (2)$$

where A is the concentration of the solution ($moll^{-1}$), B is the current density ($Amm^{-2}$), and Y is the hydrogen production rate ($Lmin^{-1}$).



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Estimated Regression Coefficients for Rate(L/min)

Term                                  Coef    SE Coef        T      P
Constant                            0.1209   0.03267     3.700  0.000    Line1
Current density                     5.9800   0.39750    14.941  0.000    Line2
Dis                                 0.0011   0.00059     1.819  0.070    Line3
Conc                                0.1782   0.02004     8.888  0.000    Line4
Current density*Current density   33.0744   2.44226    13.543  0.000    Line5
Dis*Dis                             0.0000   0.00000     0.219  0.831    Line6
Conc*Conc                           0.0080   0.00721    11.149  0.000    Line7
Current density*Dis                -0.0010   0.00192    -0.506  0.614    Line8
Current density*Conc                0.9867   0.10860     9.041  0.000    Line9
Dis*Conc                            0.0000   0.00011     0.364  0.716    Line10

S = 0.04024   R-Sq = 90.7%   R-Sq(adj) = 90.1%
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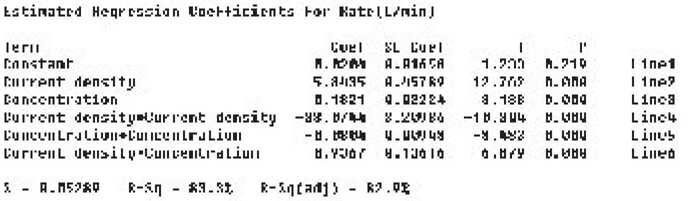
Fig. 3 The result of Response Surface Regression: Rate ($Lmin^{-1}$) versus Current density ($Amm^{-1}$), Distance (mm) and Concentration ($moll^{-1}$)



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Estimated Regression Coefficients for Rate(L/min)

Term                                  Coef    SE Coef        T      P
Constant                            0.0204   0.01650     1.233  0.219    Line1
Current density                     5.8495   0.45789    12.772  0.000    Line2
Concentration                       0.1821   0.02224     8.188  0.000    Line3
Current density*Current density   -33.0744   3.20986   -10.304  0.000    Line4
Concentration*Concentration        -0.0804   0.00949    -8.482  0.000    Line5
Current density*Concentration       0.9367   0.13616     6.879  0.000    Line6

S = 0.05280   R-Sq = 83.3%   R-Sq(adj) = 82.9%
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Fig. 4 The result of Response Surface Regression: Rate ($Lmin^{-1}$) versus Current density ($Amm^{-1}$) and Concentration ($moll^{-1}$)

The model of Eq.2 is suitable for calculating the optimal hydrogen production rate of NaOH solution and the coefficient $R^2$ and adj-$R^2$ equal to 83.3% and 82.9%, respectively. Eq. 2 is a correlation among the main factors and interaction factors that affect the hydrogen production rate. Therefore, Eq. 2 is reliable when the current density and the solution concentration are in the considered range from 0.015 to 0.12 $Amm^{-2}$ and 0.1 to 2.0 $molL^{-1}$, respectively.

For the interaction factors affecting the hydrogen production rate, the results are shown in Figs. 5 and 6. It has been found that the interaction of co-factors effect contributes to the process of increasing gas quantities.

Fig. 5 shows the mean hydrogen production rate on the y axis by varying the concentration on the x axis. It has been found that the higher current density and concentration result in an increasing hydrogen production rate. A variation of concentration affects the hydrogen production rate significantly in the range lower than 1.0 $molL^{-1}$. In addition, Fig. 6 demonstrates the contour of response surface of hydrogen production rate, the level of the factors or the area in contour which is the amount of hydrogen production rate that occurs when the current density and concentration are fixed.

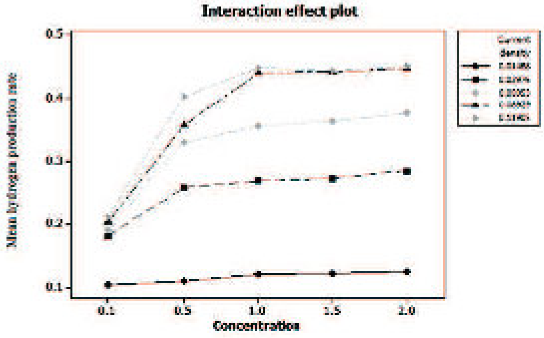

Fig.5 The mean hydrogen production rate on the y axis by varying the concentration on the x axis

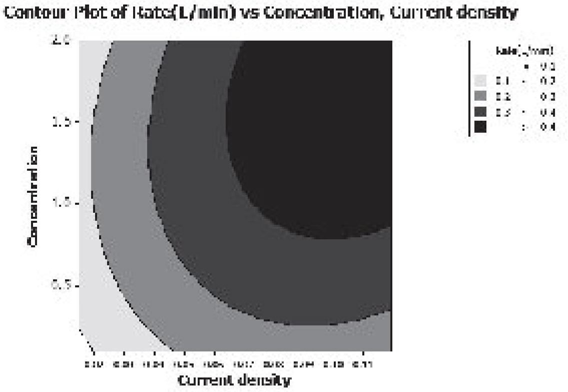

Fig.6 The contour plots of a response surface of hydrogen production rate (Lmin$^{-1}$)

According to the experimental results, the efficiency of the system is 15.35% when 2.0 molL$^{-1}$ NaOH solutions is used with the input electricity of 40 Amp and the distance between the electrodes is 145 mm. This is the best case of hydrogen production. The efficiency is calculated from $\eta$ = HV / (Power input) where HV (Heating Value) is 121.0 MJkg$^{-1}$, volume of gas is 0.0001m$^{3}$, density of gas at atmospheric is 0.0899 kg m$^{-3}$, voltage is 14.6 Volt and the time is 12.13 seconds. So HV is (121.0 × 10$^{3}$ (kJkg$^{-1}$)) × (0.0001 (m$^{3}$)) × (0.0899 (kgm$^{-3}$)) which is equal to 1087.79 J, and the power input is 40 (Amp) × 14.6 (V) x 12.13 (s) which is equal to 7083.92 kJ. For the worse case of hydrogen production, the efficiency of the system is 23.88%.

The optimization of hydrogen production rate is 0.4753 Lmin$^{-1}$ at current density of 0.1124 Amm$^{-2}$ and concentration of 1.7730 molL$^{-1}$ which has been established based on the initial conditions where

current density = 0.01488 Amm$^{-2}$, concentration = 0.1 molL$^{-1}$ and distance = 55mm

The boundary conditions are

current density = 0.01488 Amm$^{-2}$, concentration = 0.1 molL$^{-1}$ and distance = 55mm current density = 0.11905 Amm$^{-2}$, concentration = 2.0 molL$^{-1}$ and distance = 145mm.

It is noted that the distance between electrodes is fixed since it does not affect the hydrogen production rate as aforementioned.

## Conclusion

The experimental design technique is used in this work to determine the correlation among relative factors through statistical methods. Among several factors, it is found that the most important factor is the current density since a higher current density discharges a larger amount of electrons. These electrons take part in electrochemical reactions; thereby enhancing the amount of hydrogen production. In addition, the solution concentration is also important as it allows the convenient passage for ions and electrons. The hydrogen production rate is increased gradually until it reaches a constant value as the solution is saturated. Efficiency is inversely proportional to the hydrogen production rate. By consuming 584 Watt of electricity, the hydrogen production rate reaches its highest with the efficiency of 15.35%. However, when hydrogen production efficiency of the system is 23.88%, 51.55 Watt of electricity is consumed. A detailed study on effects of temperature and resistance of solution are suggested for the future work.

## Acknowledgements

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