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EFFECT OF LORENTZ FORCE ON HYDROGEN PRODUCTION IN WATER ELECTROLYSIS EMPLOYING MULTIELECTRODES

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Key words: multielectrodes, Lorentz force, water electrolysis, hydrogen production.

ABSTRACT

The aim of this study was to investigate high-efficiency hydrogen production through water electrolysis by using multiple electrodes; the investigated approach can be applied in industry. In this study, three groups of parallel electrodes were used to conduct experiments and research related to water electrolysis parameters. During electrolysis, we introduced Lorentz forces to an electrolytic cell to determine whether the multielectrode mode is identical to the single-electrode mode regarding increases in hydrogen production.

The results showed that a multielectrode group instantly increased gas production. In addition, introducing an external upward magnetic field into an electrolytic cell increased gas production at various concentrations during electrolysis. A downward magnetic field increased gas production in a 10-wt.% KOH electrolyte; this phenomenon does not occur in single-electrode electrolysis. According to IV curves, the decomposition voltage of the electrodes was between 1.87 and 1.93 V. A high-speed camera was used to photograph the magnetic flow field, gas-bubble-layer thickness, and the rising speed of the gas bubbles with and without a Lorentz force. An upward Lorentz force (FL(up)) improved all electrolysis effects, increased the gas bubble layer thickness, and increased the rising speed of the gas bubbles. The current difference increased to a maximum of approximately 370 mA/cm^2 when an electrode spacing of 5 mm and a 10-wt.% KOH electrolyte were used. Applying an FL(up), a KOH electrolyte concentration of 20 wt.%, and an electrode spacing of 3 mm increased the hydrogen gas yield by between 2.4% and 4%, according to the amount of accumulated gas measured using gas mass flow.

I. INTRODUCTION

Hydrogen is considered a potential future energy carrier. Among several methods of hydrogen production, water electrolysis is the most common, because it produces hydrogen with a high degree of purity. Therefore, enhancing the efficiency of water electrolysis is a prominent research topic. Several previous publications have investigated the influences of electrolytic parameters on the hydrogen production rate in the water electrolysis process; these include different electrodes (Kaninski et al., 2006; Dubey et al., 2010; Chauveau et al., 2011), the interelectrode distance (Nagai et al., 2003; Stojic et al., 2003), flowing effect (Licht et al., 2001), different electrolytes (Souza et al., 2006 and 2007), solution temperature (Chauveau et al., 2011), addition of active compound (Nikoli et al., 2010), and the optimal conditions for water electrolysis system (Zhang et al., 2010).

Bund et al. (2003) experimentally investigated the limiting current density in various electrode areas and directions of the magnetic field under a stable magnetic field of 1 T. Because of the influence of magnetohydrodynamics (MHD), different magnetic directions resulted in upward Lorentz forces (FL(up)) or downward Lorentz forces (FL(down)). This affected the corresponding natural convection and mass transport. Weier et al. (2005) measured the maximal velocities of an electrolytic solution by using digital particle image velocimetry, and the convective flows caused by applying Lorentz forces in different directions were upward and downward.

Few studies have discussed the effect of a magnetic field on the hydrogen production rate in water electrolysis. Koza et al. (2011) demonstrated that this effect was characterized by a reduction of the mean bubble size and an increase in the density of the bubble-size distribution in a magnetic field. It should be

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possible to improve the energetic efficiency of hydrogen production substantially through water electrolysis in a magnetic field. Wang et al. (2010) performed water electrolysis galvanostatically by using a super gravity field. This field facilitated reducing high cell voltages, especially under conditions of high gravity and at high current densities. Energy savings were between 9% and 17%. Iida et al. (2007) and Matsushima et al. (2007) investigated the I-V curve of water electrolysis by using various electrode distances and electrolytic solutions and applying magnetic fields. According to the I-V curve, the voltage difference with and without magnetic force became substantial when using a short electrode distance, low solution concentration, and strong magnetic field, where the convection phenomenon is enhanced by MHD.

Numerous variables can improve the effectiveness of electrolysis. Among all variables, magnetic force is among the most crucial and therefore worth further study. Without consuming additional energy, magnetic disturbances can increase the amount of hydrogen and oxygen ions and enhance the response mechanism of electrons, thereby improving the efficiency of water electrolysis. To enhance the effect of the magnetic force, nickel (ferromagnetic) was used as an electrode material in this study; furthermore, the use of three sets of parallel electrodes is similar to the industrial mode of hydrogen production. In addition to being cheap and strongly corrosion resistant, a nickel electrode is paramagnetic. Paramagnetic material easily generates a spontaneous interior magnetic field under the influence of an exterior magnetic field. Consequently, the MHD effect is enhanced and leads to an increase in electrolysis efficiency because of the interior and exterior magnetic fields. When a magnetic field is added to enhance the electrolysis efficiency, the direction of ion movement changes because the magnetic and electric fields are orthogonal. Ion particles are affected by Lorentz forces. In this study, the following experimental parameters were used: electrode distances of 3, 5, and 10 mm, electrolyte concentrations of 10-40 wt.%, and upward and downward directions of magnetic force. We used a high-speed camera to observe bubble phenomena (flow field, rising velocity, and layer thickness) and investigated electrolytic performance to understand how hydrogen production is affected by using multiple electrodes, using a single electrode, and applying magnetic force. We anticipated that the experimental results would enable identifying adequate parameters for achieving optimal hydrogen production through water electrolysis.

II. THEORY

In water electrolysis, two electrodes, through which direct current (DC) flows, are immersed in electrolysis liquid. Consequently, water is decomposed into hydrogen and oxygen gases. The reactions of the anode and cathode in both neutral and alkali solutions are shown in formula (1) and (2); the total reaction is described in formula (3). The overall reaction potential E is the standard reversible potential , which is -1.229 V at 25°C.

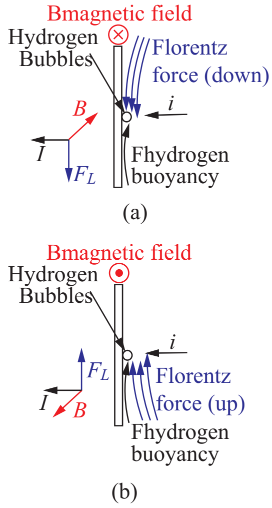


Fig. 1. The effect of the flow field near the cathode. (a) downward Lorentz force, (b) upward Lorentz force.

$$\text{Cathodic reaction: } 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (1)$$

$$\text{Anodic reaction: } 2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \quad (2)$$

$$\text{Total reaction: } H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (3)$$

1. Lorentz Force

A Lorentz force is exerted on a charged particle moving in an electromagnetic field and is shown in formula (4).

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \quad (4)$$

Where F is the Lorentz force, q is the charge of the particles, E is the electric field intensity, B is the magnetic flux density, and v is the particle velocity. The reason for adding a magnetic field to an electric field is to increase the electrolysis rate by forcing charged particles to move in the direction perpendicular to the magnetic lines, when the magnetic equivalent lines and electric equivalent lines are orthogonal. Therefore, the direction of particle movement changes because of the Lorentz force. An optimal design of magnetic and electric directions provides a uniform flow field, a suitable ion distribution between electrodes, and improved electrolysis rate. This is consistent with Eq. (4), which can be written as $|\vec{F}| = q|\vec{v}||\vec{B}|\sin\theta$, where θ is the angle between $\vec{B}$ and $\vec{v}$. When $\vec{v} \perp \vec{B}$, $|\vec{F}| = q|\vec{v}||\vec{B}|$, and when $\vec{v} \,//\, \vec{B}$, $F = 0$. Therefore, only a suitable magnetic field direction exerts a Lorentz force and enhances the convective phenomenon of MHD in water electrolysis.

The electromagnetic effects of Lorentz forces can be explained by Ampere's right-hand rule. In this study, the effect of the flow field at the cathode was defined as shown in Fig. 1(a):

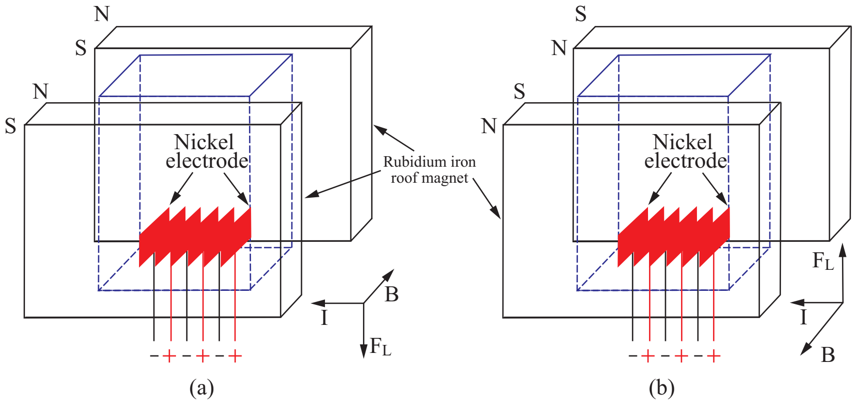


Fig. 2. The experimental set-up of the electrolytic cell. (a) downward Lorentz force, (b) upward Lorentz force.

adding a magnetic force produces a downward Lorentz force, and convection of the electrolyte counteracts the floating power of hydrogen bubbles and exerts a negative effect. As shown in Fig. 1(b), when a magnetic force is added and an FL(up) is applied, electrolyte convection is oriented in the direction of the floating power of hydrogen bubbles, positively affecting hydrogen production through electrolysis and reducing electrochemical polarization; these "positive" and "negative" effects are crucial factors in increasing the electrolysis rate. Detailed expression for effect of magnetic field on the ion and electron convection cycle was reported in our previous publication (Lin et al., 2011).

2. Current Efficiency

In water electrolysis, the actual electrical power that is required exceeds the theoretical required power. Because of resistance in the electrolytic solution and electrodes caused by side and inverse reactions and an impurity of electrode materials, the current efficiency is always below 100%.

Hydrogen production is proportional to the electric current applied during electrolysis. Therefore, this study used linear sweep voltammetry in the range of 1 to 4 V to measure the corresponding I-V curves and compare the currents with and without magnetic fields. The current difference is thus defined as follows:

$$\text{Current difference}: \ \Delta I = I_{magnetic} - I_{no\ magnetic} \quad (5)$$

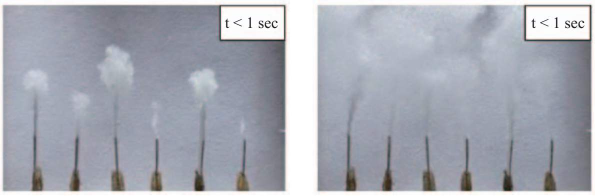
III. EXPERIMENTAL

The electrolytic cell in this experiment was a 12 mL chamber composed of anti-acidic and anti-alkaline acrylic material. Fig. 2 shows the experimental setup of the electrolytic cell. The magnetic direction was perpendicular to the electric current, and the electrode plates consisted of nickel and covered an area of 10 × 10 mm. Nickel electrodes are ferromagnetic, anti-oxidizing, and anti-corrosive; when they are exposed to air, an oxide protection layer is formed. An aqueous KOH solution was used as the electrolyte because it exhibits a higher hydrogen dissociation rate and no side products than other types of electrolyte, such as HCl, NaOH solutions do. Three sets of parallel electrodes with positive and negative arrangements were used mainly to increase gas production, meeting industrial requirements for high-efficiency hydrogen production. In addition, the amount of hydrogen production was investigated after an external magnetic field was added during electrolysis.

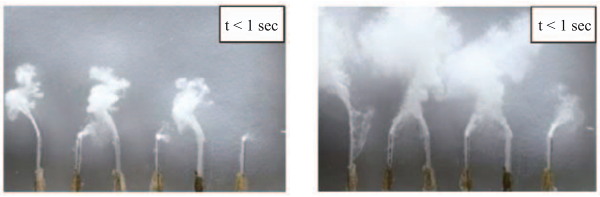
In this experiment, the effects of the following distinct parameters on the electrolysis current density were investigated: the electrolyte concentration, electrode distance, applied voltage, and magnetic field. The AUTOLAB PGSTAT302N potentiostat of the Dutch company ECO was used to analyze the electrolytic performances of water electrolysis at various electrode distances and specific electrolyte concentrations with and without a Lorentz force. A high-speed camera recorded the effects of various parameters on the flow field, rising velocity, and layer thickness of gas bubbles. The applied voltage was varied from 1.0 to 4.0 V, and the electrolyte concentrations were 10, 20, 30, and 40 wt%. The electrode distances were set to 2, 5, and 10 mm, and the magnetic strength was fixed at 4.5 T. The magnetic direction was changed by alternating the position of the magnetic poles (NS). According to Fig. 1, the direction of the Lorentz force varied according to the position of the NS magnetic poles; consequently, the direction of flow of the magnetic fluid changed, affecting the direction of gas flow and changing the efficiency of gas production. Furthermore, to understand the difference in the hydrogen gas yield between a single-electrode mode and a multielectrode mode, gas flow was used to collect the actual hydrogen yield according to the electrolyte concentration (20 wt.% of KOH), working voltage (3 V), and electrode distance (3 mm).

IV. RESULTS AND DISCUSSION

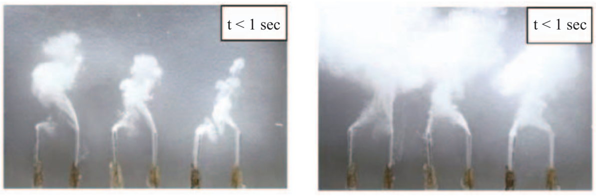
The influences of magnetic fields on hydrogen production through electrolysis were investigated by using custom-made electrolytic cells, a high-speed camera, and a pontentionstat-galvanostat. The experimental photos show the effect of MHD on the flow field. To lower the electrode polarization and the over-potential value and increase the reaction rate and the reaction electric current value in water electrolysis, we investigated how



(a) DC (no magnetic)



(b) FL(up)



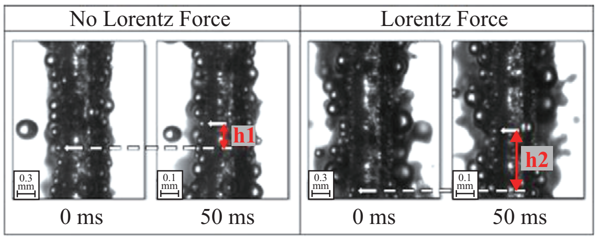
(c) FL(down)

Fig. 3. The bubble motion diagrams observed in multi-electrodes cell. (a) without magnetic field, (b) with upward magnetic field, (c) with downward magnetic field.

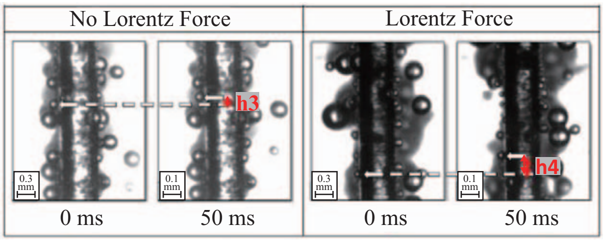
the Lorentz force caused by MHD affects ions and enhances mass transfer and convection effects. Experimental data regarding the efficiency of water electrolysis using magnetic fields are provided in the following three sections.

1. The Observation of Bubble Phenomenon under Magnetic Force

Fig. 3 shows a bubble-motion diagram of three groups of parallel electrodes at an applied voltage of 3.5 V, electrode distance of 5 mm, and KOH electrolyte concentration of 20 wt.%. During electrolysis, a high-speed camera captured the direction of the bubble motion to enable understanding how it was affected by the Lorentz force. Fig. 3(a) shows the flow fields of experiments in which no magnetic field (DC) was applied. When no Lorentz force was applied, the bubbles rose to the surface of the electrolyte and were concentrated in the upper portion of the electrolytic cell without convection. Fig. 3(b) shows the bubble motion when the direction of the Lorentz force was upward. Bubbles exhibited a convection phenomenon, and self-convection occurred in both the left and right electrodes. Because both the Lorentz force and buoyancy force were upward oriented, hydrogen bubbles escaped faster from the electrode region than they did when they were created. Fig. 3(c) shows the bubble motion when the Lorentz force was downward oriented. The generated bubbles flowed between the positive and negative electrodes. Although a convection phenomenon occurred, the buoyancy force of the hydrogen bubbles



(a)



(b)

Fig. 4. The rising velocity of hydrogen gas bubbles at various current density. (a) 0.3 A/cm^2, and (b) 0.1 A/cm^2.

and the Lorentz force were directionally opposed. Several bubbles easily remained or moved downward along the electrode.

When applying a magnetic field on the cell, the ions in solution continuously move to the electrodes. The density of ions around the electrodes is higher than average ions in the solution, and then the balance is formed around electrodes. In other words, the magnetic field can enhance the electrolyte convection, such that ion will move to electrodes not only by mass diffusion, but also by momentum convection. The electrolysis efficiency is therefore enhanced (Lin et al., 2011).

Fig. 4 shows the rising velocity of hydrogen gas bubbles and the bubble layer thickness on the cathode electrode. To observe the phenomenon of bubble growth and reduce the experimental error, the times at which bubbles were measured were only 0 and 50 ms. In water electrolysis, the cathode electrode was covered with varying diameters of hydrogen bubbles; therefore, we defined bubble diameters between 0.053 and 0.06 mm as the benchmark. Fig. 4 (a) shows the rising velocity of hydrogen gas bubbles at a current density of 0.3 A/cm^2, electrode distance of 3 mm, and measured time of 0 and 50 ms. Under these conditions, the bubbles rose to the height h1 when no magnetic field was applied and height h2 when a magnetic field was applied. Adding the magnetic field increased the velocity of rising bubbles and thereby accelerated the forward speed of the electrolytic ions and reduced polarization impedance. In addition, the layer of hydrogen bubbles on the electrode sheet thickened under the influence of the magnetic field, indicating that the reaction region of instant electrons and ions in the electrolytic cell increased; therefore, hydrogen gas production increased. Fig. 4(b) shows the rising velocity of hydrogen gas bubbles at a current density of 0.1 A/cm^2. As shown in the figure, the rising distance of the bubbles, h4 > h3, showed that the magnetic field increased the velocity of rising

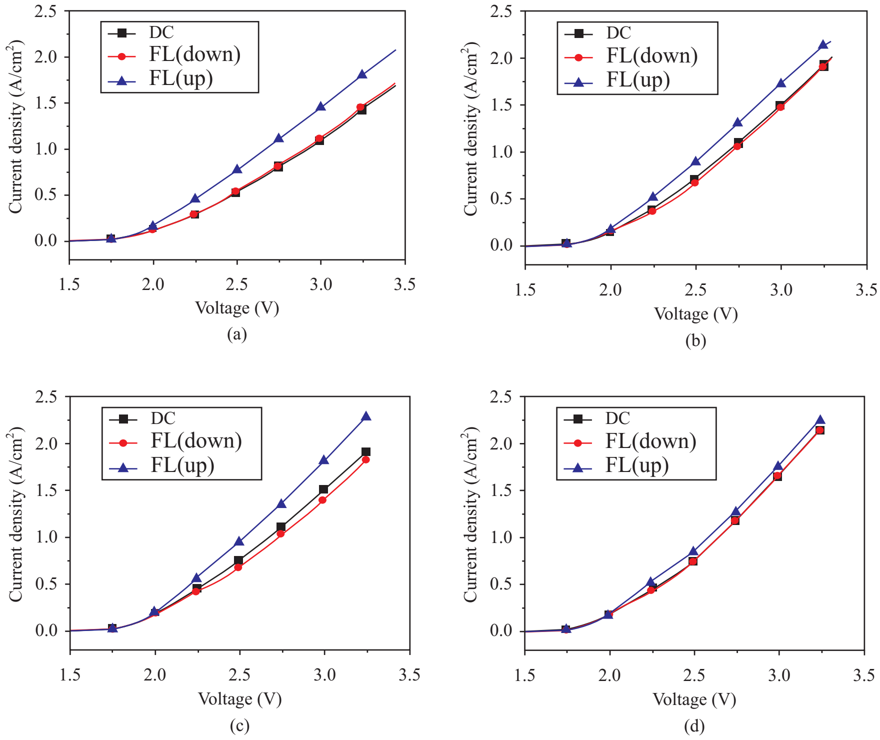


Fig. 5. The I-V curves of the electrode with the Lorentz force in various KOH electrolyte concentrations. (a) 10 wt%, (b) 20 wt%, (c) 30 wt%, (d) 40 wt%.

bubbles and the thickness of the bubble layer. Hence, the Lorentz force promoted electrolyte convection, possibly by increasing the thickness of the bubbles and the speed of bubble-layer movement, reducing the electrochemical polarization effect, and improving the overall hydrogen production capacity. The bubble motion in a magnetic field reflected the rising velocity accelerated by MHD convection. These results suggested that a magnetic field caused remarkable improvement for the surface coverage of the electrode (Matsushima et al., 2013).

2. The Effect of Lorentz Force on the Electrolytic Performance

Fig. 5 shows the effect of the Lorentz force on the I-V curve of an electrode in various KOH electrolyte concentrations. A curve exhibiting a greater slope indicates enhanced electrolysis efficiency. The slope of the I-V curve increases with the electrolyte concentration. The optimal I-V curve is obtained using a 30-wt.% KOH electrolyte; this result is consistent with those of previous studies (Zeng et al., 2010; Lin et al., 2011) that have indicated that a 20- to 30-wt.% electrolyte exhibits the highest electrical conductivity and an optimal hydration effect. When the electrolyte concentration was increased to 40 wt.%, the slope of the I-V curve only increased with small amount because of the ion concentration is very high. The effect of magnetic field on ion movement is not apparent. Adding a magnetic field during electrolysis caused a magnetic fluid dynamics effect, which affected the electrolyte flow field, accelerated ion movement, and increased the rising speed of the bubbles when an FL(up) was applied. Therefore, the slope of the I-V curve when an FL(up) was applied was greater than that when DC only and an FL(down) were applied.

Fig. 6 shows the electrolytic performance of the electrode with or without an FL(up) at various interelectrode distances (i.e., 3, 5, and 10 mm), a magnetic strength of 4.5 T, and an electrolyte concentration of 20 wt%. As shown in Fig. 6(a), when an FL(up) was applied, using a shorter electrode distance resulted in an electrolytic efficiency superior to that of a longer distance. The optimal I-V curve occurred at an electrode distance of 3 mm when a FL(up) was applied. According to water electrolytic theory, its decomposition voltage is 1.23 V; however, energy losses (overpotential) are unavoidable during electrolysis. Therefore, the actual decomposition voltage is the sum of the theoretical decomposition voltage and the overpotential. Fig. 6(b) shows a partially enlarged view of the I-V curves; the decomposition voltage of the parallel electrodes is the value at the intersection of the zero line of the current density and the slope of the I-V curve. According to the figure, the decomposition voltage was a value between 1.87 and 1.93 V with or without a magnetic field at the electrode distances. The difference between these decomposition voltages was small. However, adding a magnetic field in a cell improved the efficiency of electrolysis.

3. The Effect of Lorentz Force on Electrolytic Efficiency and the Yield of Hydrogen Gas

In order to understand the effect of Lorentz force on the elec-

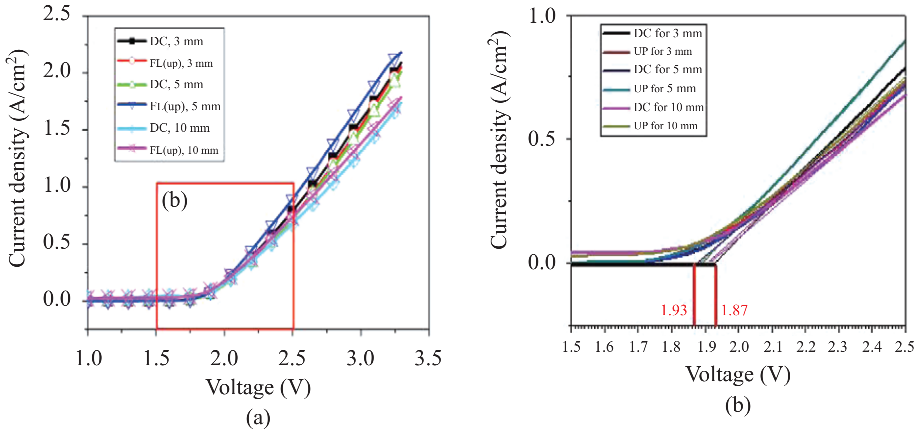


Fig. 6. The electrolytic performance of the electrode with or without FL(up) at various electrode distances. (a) the I-V curve, (b) the decomposition voltage.

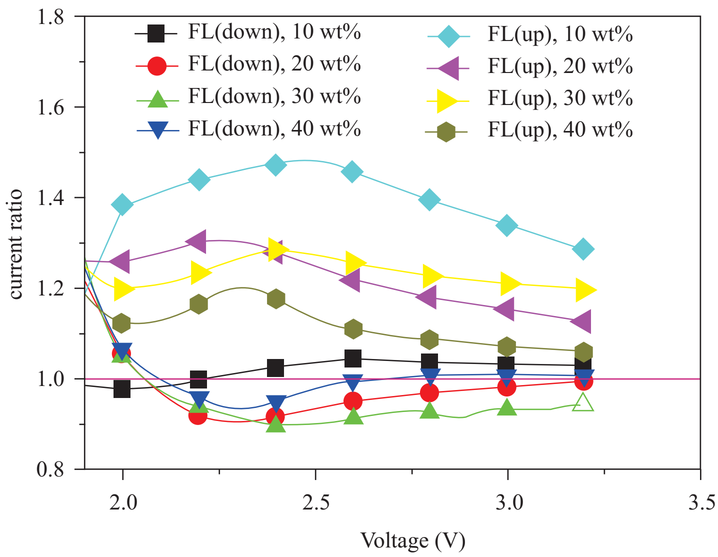


Fig. 7. The relationship between current ratio and voltage under the action of the Lozentz force. (Inter-electrode distance of 5 mm, the magnetic force of 4.5T).

trolytic efficiency m we defined a current ratio as formula (6).

$$\text{Current ratio： } R = I_{magnetic} / I_{no\ magnetic} \quad (6)$$

Fig. 7 shows the relationship between the voltage and the current ratio applied at an electrode distance of 5 mm, a magnetic force of 4.5 T, and a working voltage of 3 V. Applying an FL(up) on the cell, the figure reveals that the current ratio first increases and then decreases as the voltage increases for four different concentrations. If we compare the optimal current ratios for four curves, the 10 wt% electrolyte shows a highest value of 1.5, the 40 wt% electrolyte shows a lowest value of 1.2, while both the 20 and 30 wt% electrolytes reveal the medium value of around 1.3. The results demonstrate that when the electrolyte concentration is only 10 wt%, the enhancement on electrolyte convection by magnetic field is very high. Therefore, the current ratio increases dramatically. However, for the 40 wt% electrolyte, the ion concentration is very high. The effect of magnetic field on ion movement is not apparent. That's the reason why their current ratios only increase in small amount. For the 20 wt% and 30 wt% electrolytes, their current ratios show very similar values. At low voltage part, 30 wt% electrolyte shows a lower current ratio than 20 wt% electrolyte. This is due to larger enhancement on electrolyte convection by magnetic field for 20 wt% electrolyte. At high voltage part, 30 wt% electrolyte reveals higher current ratio than 20 wt% electrolyte. This may be due to both concentration and magnetic field having effect on the enhancement of current ratio for 30 wt% electrolyte. Applying a FL(down) on the cell, all the current ratios are less than 1 except the 40 wt% electrolyte at high voltages. In summary, introducing an FL(up) in the cell effectively improved the electrolysis efficiency.

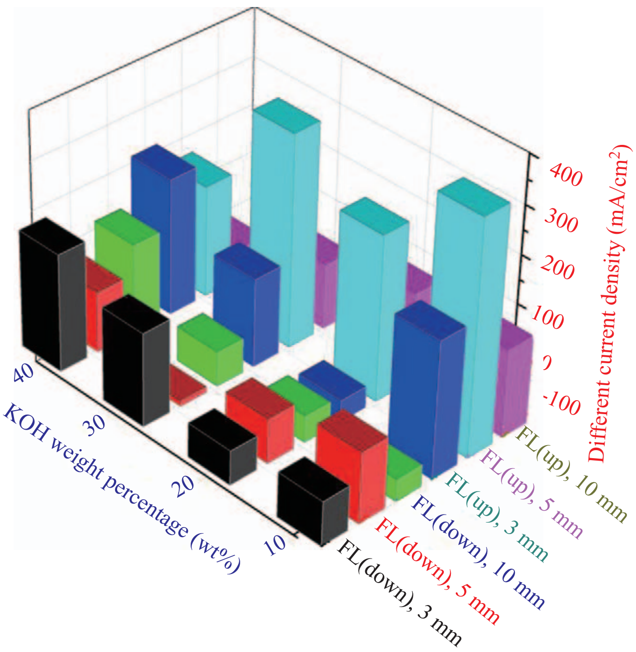


Fig. 8. A 3D diagram to show the effects of magnetic field, electrode distance and KOH concentration on the current densities.

However introducing FL(down) in the cell has negative effect on the electrolysis efficiency.

Fig. 8 is a 3-D diagram to show the effects of magnetic field, electrode distance and KOH concentration on the current densities. The figure shows an optimal current difference of approximately 370 mA/cm^2 in a 10 wt% KOH electrolyte subjected to an FL(up), indicating that the impedance problem caused by a low electrolyte concentration was effectively mitigated by the Lorentz force. For all experimental variables, applying an FL(up) increased the current difference. However, in a 40-wt% KOH electrolyte, the current density difference was positive when both (up and down) directions of the Lorentz force were applied. The Lorentz force caused a convection phenomenon during water electrolysis, and therefore the ion transfer in the electrolyte and electron shift on the electrode surface were accelerated. Polarization impedance was reduced, and, therefore, the hydrogen production efficiency increased.

To understand the difference in the hydrogen yield produced by a single electrode group and that produced by a multielectrode group, gas mass flow was used to collect hydrogen gas during electrolysis. The experimental parameters included a KOH electrolyte concentration of 20%; a fixed working voltage of 3 V; a fixed electrode spacing of 3 mm; an accumulated time of 30 min; and 2, 4, and 6 sheets of electrodes. First, in the absence of a magnetic field, the hydrogen gas yield was measured for three quantities of electrode sheets arranged in order as follows: 150 CC (2 sheets) < 310 CC (4 sheets) < 434.4 CC (6 sheets). When a magnetic field was applied, the hydrogen gas yield was measured for three quantities of electrode sheet arranged in order as follows: 156 CC (2 sheets) < 318 CC (4 sheets) < 446 CC (6 sheets). The results show that the yield of hydrogen gas increased with the number of electrodes, but the increase did not occur in a certain ratio. In addition, applying an FL(up) increased the yield of hydrogen gas; the rate of hydrogen gas increase was between 2.4% and 4%. Therefore, introducing an FL(up) into the cell and adopting an appropriate multielectrode modular design facilitates increasing the yield of hydrogen gas.

V. CONCLUSION

The multielectrode group for hydrogen production used in this study was similar to that used in industrial applications. The hydrogen yield obtained using a multielectrode group (6 sheets) was 2.2-2.9 times higher than that obtained using a single electrode group (2 sheets). The decomposition voltage achieved using a multielectrode group was between 1.87 and 1.93 V, which is considerably close to that of a single electrode group. No substantial increase in the decomposition voltage was evident when the number of electrode sheets was increased. Applying a magnetic field to an electrolytic cell causes an MHD effect, which promotes the convection phenomenon. This accelerates ion transfer in the electrolyte and electron shift on the electrode surface. A decrease in polarization impedance leads to an increase in electrolysis reaction. Disturbance of the magnetic field produces several effects: first, the I-V curve slope increases, indicating that the current density increases; second, the reaction bubble layer on the electrode sheet thickens, indicating that the valid response range increases; and, third, gas bubbles break faster and move away from the electrode surface faster. These phenomena effectively improve the amount of hydrogen production. For all experimental variables, applying an FL(up) increased all current differences; the optimal current density difference was 370 mA/cm^2 at an electrode distance of 5 mm and a 10-wt.% electrolyte concentration. Even at a 40-wt.% electrolyte concentration, applying an FL(down) increased the current difference, indicating that the magnetic force mitigates the problem of impedance, which is caused by a high electrolyte concentration. In conclusion, increasing the number of electrode sheets increases the yield of hydrogen gas, and applying an FL(up) to an electrolytic cell exerts a positive effect.

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