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Hydrogen Production by Water Electrolysis with Low Power and High Efficiency Based on Pre-Magnetic Polarization

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Abstract: In this paper, a method of efficient hydrogen production using low-power electrolysis based on pre-magnetic polarization was proposed in order to improve the rate of hydrogen production by water electrolysis, with reduced energy consumption, molecular polarity, and stress–strain characteristics of distilled water under the condition of a pre-magnetic field. By constructing a microphysical model of hydrogen proton energy-level transition and a macroscopic mathematical model corresponding to magnetization vector-polarization hydrogen proton concentration in the pre-magnetic field, the ionic conductivity, electrolyte current density, interelectrode voltage, and hydrogen production efficiency under a varying magnetic field were qualitatively and quantitatively analyzed. In addition, an adjustable pre-magnetic polarization hydrolyzing hydrogen production test platform was set up to verify the effectiveness of the proposed method. The repeated test results, within a magnetic field strength range of 0–10,000 GS, showed that the conductivity of distilled water after pre-magnetic polarization treatment increased by 2–3 times, the electrolytic current density of the PEM (Proton Exchange Membrane) increased with increasing magnetic field strength, the voltage between the poles continuously decreased, and the hydrogen production rate was significantly improved. When the magnetic field strength reached 10,000 GS, the rate of hydrogen production by the electrolysis of distilled water increased by 15–20% within a certain period of time.

Keywords: pre-magnetic polarization; hydrogen production rate; electrical conductivity; current density



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1. Introduction

To cope with the challenges of climate security and to promote the low-carbon, green, and sustainable development of the global economy, China, the European Union (EU), Japan, South Korea, and several other major economies have successively announced their own carbon neutrality goals; thus, the carbon reduction and decarbonization process of the energy industry will be further accelerated. As an efficient and undefined ideal secondary energy, hydrogen has the advantages of no pollution, recyclability, and high calorific value per unit mass. It can directly convert chemical energy into electric energy through fuel cells and will be an important support when building a clean-energy society in the future [1,2]. At present, the mainstream hydrogen production technology mainly includes fossil energy hydrogen production (represented by coal and natural gas), industrial by-product hydrogen production (represented by the chlor-alkali industry and coke oven tail gas), and multi-energy complementary hydroelectricity hydrogen production (represented by clean energy such as water and light). Among these, hydrogen production by water electrolysis has been widely noted by the majority of scientific research institutions and scholars for its advantages of having rich raw materials, as well as being green, clean, and low-carbon [3,4].

However, the production of hydrogen by water electrolysis accounts for less than 10% of the total production of industrial hydrogen in China at present [5]. The main problems

faced by the development of hydrogen production by water electrolysis technology at present are its high energy consumption and low energy-exchange efficiency. At the 2020 global hydrogen energy summit, Professor Zhang JiuJun, academician of the Academy of Science of the Royal Society of Canada, pointed out that most of the present hydrogen production methods using water electrolysis have an energy efficiency of about 50%, and the consumption of electric energy is relatively high. Professor Zhang mentioned that improving the efficiency and reducing the cost of hydrogen production has become a hot issue that urgently needs to be solved. Therefore, a large number of scientific research institutions and scholars have begun to study the changes in various physicochemical characteristics in water electrolysis, and adopted various auxiliary methods such as super gravity [6], ultrasonic [7], and magnetic fields [8], attempting to mitigate the above problems by enhancing the performance of electrolytic cells [9].

Some scholars have studied the influence of an external magnetic field in the process of hydrogen production using the electrolysis of water and have obtained good results. For instance, according to the research conducted by T-Iida et al. [10], after placing the whole electrolyzer in the magnetic field, the electrolytic cell voltage significantly decreased due to the reduction in mass transfer loss and electrolytic resistance. In addition, the relationship between electrolytic cell characteristics and magnetic flux intensity was obtained. X. He [11] established a magnetohydrodynamics (MHD) model of electrolyte under the action of magnetic field, and designed the experiment to prove that adding a certain size of magnetic field could improve the electrolytic efficiency of the electrolyzer. S. Jing et al. [12] developed a system that was capable of producing a repetitive, pulsed, high magnetic field, and improved the performance of an Nd–Fe–B electrocatalyst in an alkaline water electrolyzer. H.M. et al. [13] observed the magnetic field's effect on electrode bubble coverage using a transparent electrode, and found that the magnetic field's effects became more evident with increasing working current density. M.F. Kaya et al. [14] displayed the positive effects of different magnetic fields on the performance of a PEM electrolyzer under a variable water flow. In addition, at a higher limit current diffusion value, the introduction of a magnetic field can improve the mass transfer inside the electrolytic cell by increasing the convection of the electrolyte, thereby improving the performance of the electrolytic cell [15–17].

The influence of the applied magnetic field on the process of hydrogen production by electrolysis has been analyzed in detail in the above literature, and some achievements have been achieved. However, this research focuses on analyzing the effect of a magnetic field on electrode material and bubble rate during electrolysis. There is a lack of research on the development of and dynamic variation in the hydrogen proton micropolarization process in electrolytes, and the effect of circulating water velocity on hydrogen production rate. In addition, the external magnetic field relies on electricity for generation, which increases the electrolytic energy consumption. Therefore, this paper studies the molecular polarity and stress–strain characteristics of distilled water in a pre-magnetic field, proposes an efficient hydrogen production method using low-power water electrolysis based on pre-magnetic polarization, and demonstrates this method through experiments. This study can not only supplement and improve the existing hydrogen production using the water electrolysis system, but also provides a new idea for efficient hydrogen production using low-power electrolysis.

2. Theoretical Analyses

The effect of the magnetic field on water molecules in the pre-magnetic polarization treatment of distilled water is schematically shown in Figure 1.

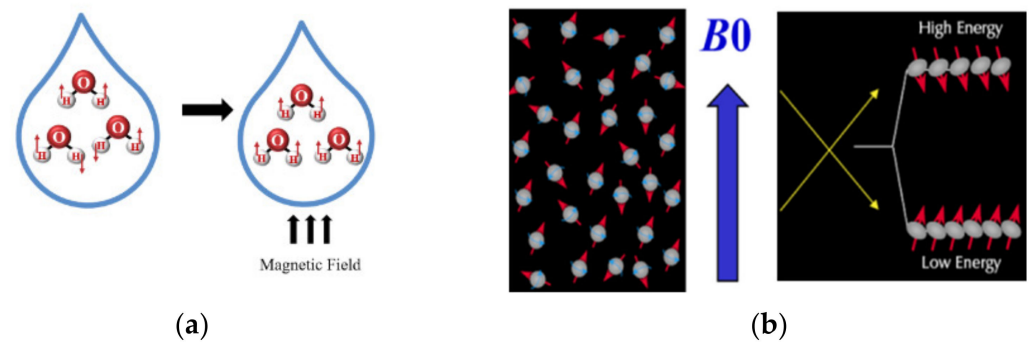


Figure 1. Effect of magnetic field on water molecules: (a) Reorientation of proton spin under magnetic field effect; (b) sketch of energy-level splitting of hydrogen proton.

From the microscopic perspective, according to the two different spin directions of hydrogen protons, water molecules simultaneously have paramagnetic and diamagnetic behaviors [18,19]. Due to the diamagnetic behavior of water, when an external magnetic field is applied, the positive and negative charges will be subjected to the action of forces in the opposite direction. Then, the number of intermolecular hydrogen bonds in the solution will decrease due to structural damage, and the opening of macromolecular water clusters will accelerate the diffusion of particles in water [20]. The Lorentz force is formulated by:

$$F = qvB \quad (1)$$

When the intensity of the pre-polarized magnetic field increases, the Lorentz force acted on particles in water will increase. The Lorentz force will act on particles in water to increase their internal energy and, as a result, the particles in water will collide more violently, and the probability of collision ionization will increase. In addition, due to the increase in the free stroke of protons, the kinetic energy possessed by the protons during collision will be larger. Hence, they can provide greater energy to overcome the potential barrier, so as to break H–O bonds and increase OH-concentration in solution. Meanwhile, the alternating action of a magnetic force on the water system can cause a macro-ordered vibration of water particles. The energy-level fracture of hydrogen protons occurs in the polarization field, forming two energy states with different proton numbers [21]. In this way, the hydrogen protons can maintain higher activity, which is conducive to the realization of efficient and rapid hydrogen production by electrolysis.

In the actual electrolysis hydrogen production process, the optimal method is to generate the same amount of hydrogen by consuming less electric energy. Therefore, the conversion efficiency of the electrolyzer is defined as:

$$\eta = \frac{QP}{IV} \times 100\% \quad (2)$$

where Q represents the volume flow rate of the evolved hydrogen in L/S; P represents the pressure of the evolved hydrogen in Pa; I represents the current passing through the electrolyzer in A; and V represents the inter-electrode voltage of the electrolyzer in V.

It can be seen from (2) that the more hydrogen is produced by the electrolysis of electric energy per unit power, the higher the conversion efficiency of the electrolyzer. According to Faraday's laws of electrolysis, under ideal conditions, the current effect of water electrolysis is 100%. Thus, (2) is deformed according to the following formulas:

$$\begin{cases} Q = 22.4 \times \frac{1}{nF} \\ \eta = \frac{QP}{IV} \times 100\% = 22.4 \times \frac{1}{nF} \times \frac{P}{IV} \times 100\% = \frac{P}{8614V} \times 100\% \end{cases} \quad (3)$$

where n represents the stoichiometric number of electrons consumed in the hydrogen evolution reaction ($n = 2$) and F represents the Faraday constant (96,485 C/mol).

There are only two variables, P and V , left in (3), and the gas pressure P is generally constant. When using (3) to quantitatively analyze the energy-conversion efficiency of the electrolyzer, only the variable V needs to be considered, and the energy conversion efficiency of the electrolyzer can only be improved by reducing the actual inter-electrode voltage of the electrolyzer. The essential reason for this is that, during electrolysis hydrogen production, the mass transfer process of the diffusion layer of water treated by magnetic polarization is strengthened, hence speeding up the speed of electrolysis hydrogen production.

No additional magnetic field is applied in the process of electrolytic hydrogen production after pre-magnetic polarization. According to the Stokes–Einstein formula and Nernst–Einstein equation, the following relations can be obtained:

$$\begin{cases} D = K_B T / 6\pi\eta r \\ \sigma = nq^2 D / K_B T \end{cases} \quad (4)$$

where D represents the diffusion coefficient in m^2/s ; K_B represents the Boltzmann constant in J/K ; T represents the temperature in K ; η represents the viscosity in $\text{Pa}\cdot\text{s}$; r represents the diffusion radius in m ; σ represents the ionic conductivity in S/m ; n represents the number of current carriers per unit volume; and q represents the quantity of electric charge in C .

The research shows that the viscosity of water solution will decrease after magnetic polarization [9]. According to the Raman spectrum analysis, B. Zheng et al. concluded that, after magnetic polarization, the hydrogen bond structure of water solution was destroyed, the outer shell layer of the hydrated ions fell off [20], and the hydrated ion radius was small. After magnetic polarization, when temperature and other conditions remained unchanged, the diffusion coefficient D of particles in water increased, the conductivity of the water solution also increased, and the resistivity ρ decreased; without changing the structure of the electrolyzer and the magnitude of the current, the decrease in ρ could effectively reduce the resistance over-potential, thereby reducing the actual inter-electrode voltage of the electrolyzer.

As shown in Figure 2, there are differences between pre-magnetic polarization and the conventional electrolysis hydrogen production process. Specifically, compared with traditional hydrogen production by water electrolysis, hydrogen production by water electrolysis based on pre-magnetic polarization applies a variable magnetic field to the distilled water before electrolysis. This could polarize the water molecules before entering the electrolyzer, so the protons could obtain the excitation energy provided by the magnetic field in advance. Then, when the protons enter the electrolyzer for electrolysis, they would only need a smaller electric field to become free electrons, participate in electric conduction, overcome the potential barrier, and break the hydrogen–oxygen (H–O) bond, thereby producing hydrogen.

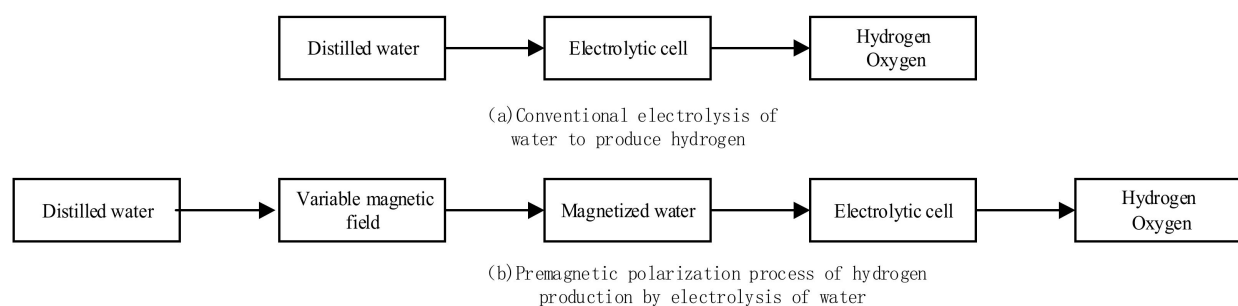


Figure 2. Comparison of conventional hydrogen production from water electrolysis and pre-magnetic electrolysis.

In summary, hydrogen production by water electrolysis under pre-magnetic polarization conditions has the following main advantages. Firstly, it can reduce the energy consumption of hydrogen production by electrolysis. To be more specific, there is a macro-

scopic orderly vibration of the magnetic force in the water system. The hydrogen protons undergo energy-level transitions in the polarized field, and the activity is enhanced. Therefore, hydrogen can be generated with less energy during electrolysis. Secondly, it can improve energy conversion efficiency. Specifically, after pre-magnetic polarization treatment, the physical properties of water have changed. Its diffusion and mass transfer process are enhanced during electrolysis, and the hydrogen production rate is accelerated under the same conditions.

3. Experimental

3.1. Experimental Equipment

To verify the feasibility of hydrogen production by water electrolysis under the condition of pre-magnetic polarization, a set of experimental equipment for hydrogen production by water electrolysis, based on strong pre-magnetic polarization, was designed (Figure 3). The equipment used an Nd–Fe–B permanent magnet to form a pre-polarization magnetic field, and the electrolyte was distilled water with an initial conductivity $\sigma \approx 0.4 \mu\text{S}/\text{cm}$. In particular, it should be noted that there are materials costs for the polarization loss rate of the permanent magnet, which is difficult to assess from the short running time of the experimental process. An intelligent peristaltic pump was used to control the flow rate and magnetic polarization time of distilled water, and the magnetic field intensity was calibrated by a Tesla meter. The change in conductivity after electrolyte magnetization was measured by a conductivity meter. Meanwhile, the PEM electrolyzer was used to produce hydrogen, and the inter-electrode voltage was measured by a high-precision bench-type digital multimeter. The changing process of hydrogen production was recorded by a high-speed camera. The relation diagram of the actual experimental equipment is shown in Figure 4.

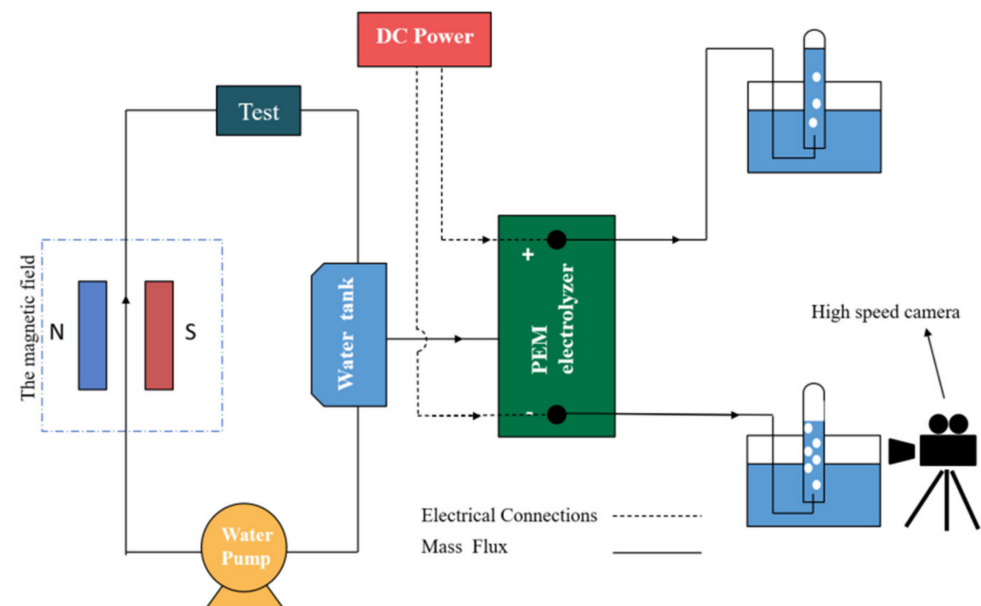


Figure 3. Schematic diagram of low-power electrolytic hydrogen production experimental device based on strong magnetic pre-polarization.

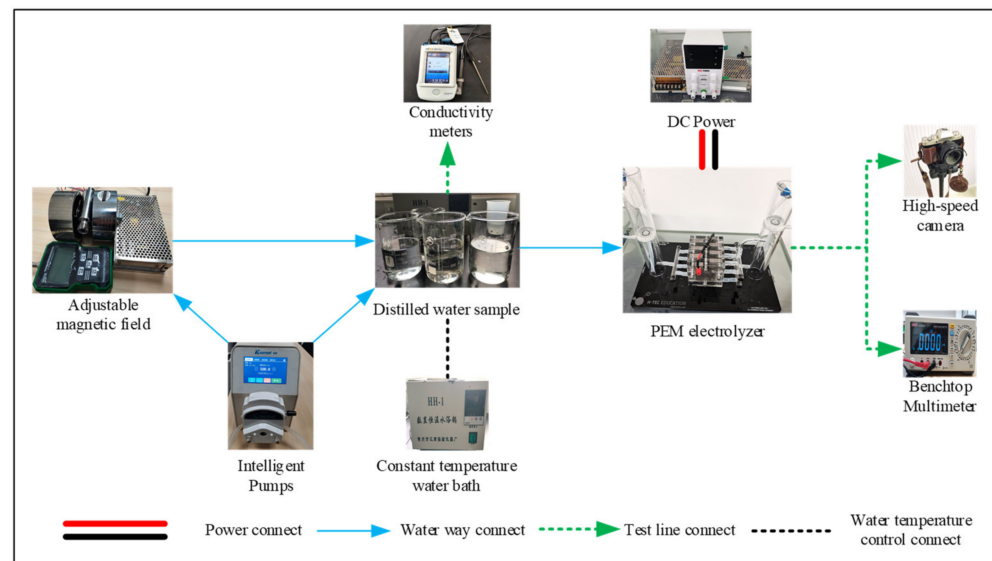


Figure 4. Schematic diagram of low-power electrolytic hydrogen production experimental device based on strong magnetic pre-polarization.

3.2. Experimental Process

The experimental process is shown in Figure 5, and is divided into two main stages. In the first stage of pre-magnetic polarization, the distilled water was divided into 50 samples, with 350 mL in each sample. Then, an adjustable pre-magnetic polarization field was set up using permanent magnets, and each sample of distilled water was controlled by the intelligent peristaltic pump to cut the magnetic line of force at a flow rate of 500 mL/min and in a perpendicular direction to the magnetic line of force. The magnetic field gradients were set as 500 GS, 1000 GS, 1500 GS, 2000 GS, 2500 GS, and 10,000 GS. After pre-magnetic polarization treatment, the changes in the properties of the distilled water, such as viscosity and hydrogen bonds, were analyzed. In addition, the conductivity of the distilled water was recorded every 1 min over 40 min during the pre-magnetic polarization. The curve chart of conductivity with the pre-magnetic polarization time was generated according to the data. After pre-magnetic polarization, the samples were statically placed, and the conductivity was measured every 1 min to observe the change trend. For the second stage of electrolysis hydrogen production, the magnetized distilled water samples were put into the PEM electrolyzer to produce hydrogen. After the samples underwent 35 min pre-magnetic polarization treatment under different magnetic field intensities, the data on the changes in their hydrogen production in the first 100 s were recorded by the high-speed camera. Finally, the experimental data were compared, the time-varying curve chart of hydrogen production from distilled water under different magnetic fields was drawn, and the changing trend was analyzed.

To minimize the data error, uncertainty (Uc) is introduced to measure the data validity, which is expressed as:

$$Uc = \sqrt{\frac{\sum_{i=1}^n (s_i - s_a)^2}{(n-1)n}} \quad (5)$$

where s_i represents the data of i th experiment; s_a represent the arithmetic mean of the data in repeated experiments; and n represent the number of experiments.

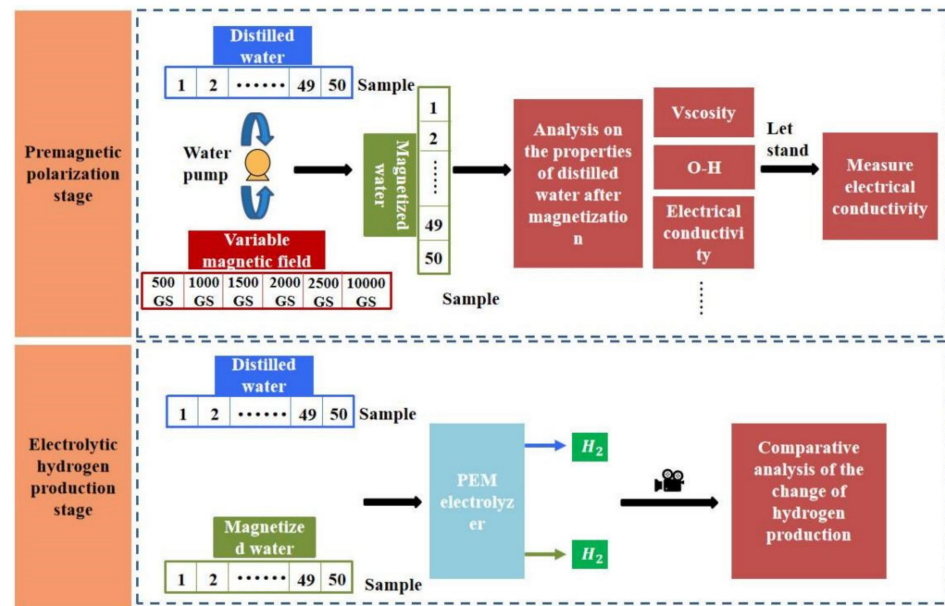


Figure 5. Experimental process diagram.

4. Results and Discussion

4.1. Conductivity Change in Magnetic Polarized Water

Figure 6 shows the changing curve of water conductivity with the magnetic polarization time after pre-magnetic polarization in different magnetic fields at 20 ± 0.1 °C. It can clearly be seen that the conductivity fluctuates and increases with increasing magnetic polarization time. The movement of particles in water molecules is irregular. After applying a magnetic field, the Lorentz force bends and breaks the hydrogen bonds between water molecules, resulting in the separation of the molecules. However, the energy generated by each cyclic polarization is small, which provides water molecules with enough time for self-repairing. By increasing the time for cyclic pre-magnetic polarization, the increase in conductivity gradually slows down.

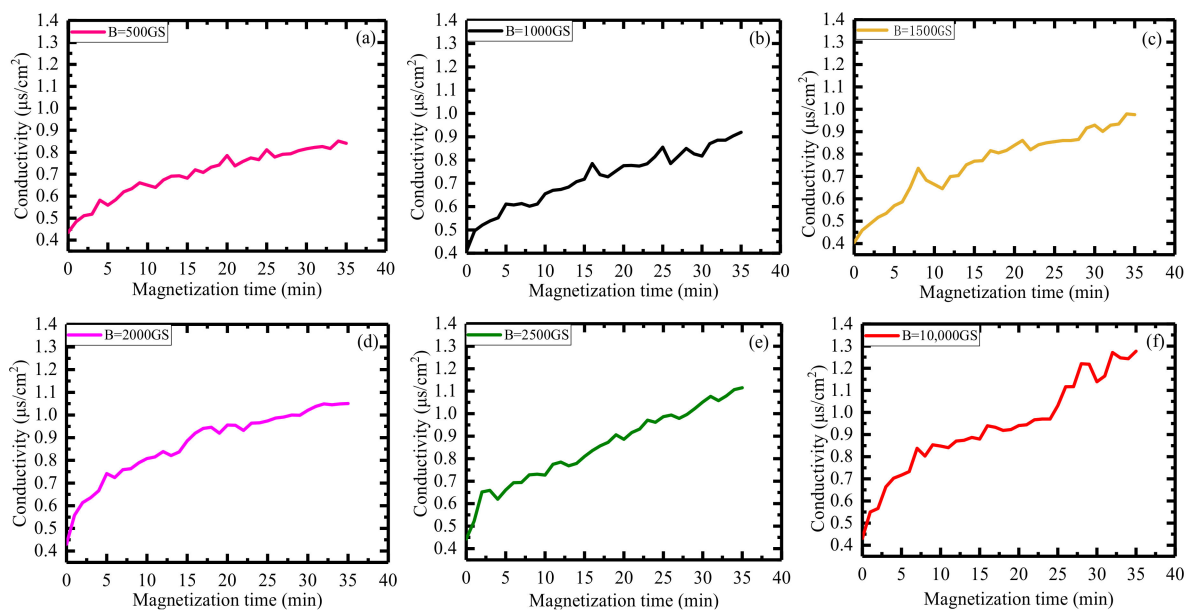


Figure 6. Change in conductivity of distilled water with magnetization time under different magnetic fields. Magnetic induction intensity: (a) 500 GS; (b) 1000 GS; (c) 1500 GS; (d) 2000 GS; (e) 2500 GS; (f) 10,000 GS.

Figure 7 is generated by the above data, processed with the non-linear curve fitting function Allometric of Origin software. It can be seen from the figure that the conductivity of distilled water obtained the fastest increases in different magnetic fields within 0–10 min, and 30 min later, the increase rate slowed down with the increase in magnetic field intensity and magnetization time.

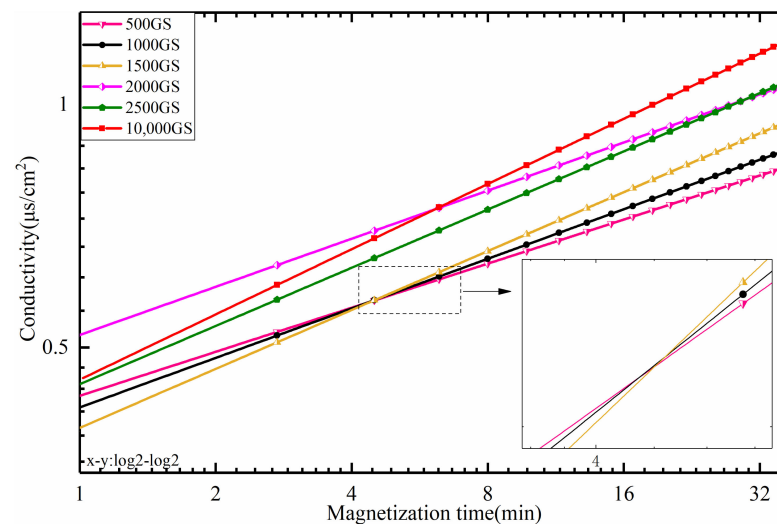


Figure 7. Fitting curve of conductivity of distilled water with magnetization time under different magnetic fields.

As shown in Table 1, it can be seen that the error between experimental data and expected value is less than 1%.

Table 1. The uncertainty of conductivity in these experiments.

	Magnetization Time (min)							
	0	5	10	15	20	25	30	35
Magnetic Field Intensity (GS)	Uncertainty of Conductivity Change (%)							
500	0.61	0.46	0.58	0.91	0.79	0.77	0.63	0.56
1000	0.86	0.38	0.78	0.92	0.85	0.72	0.64	0.68
1500	0.59	0.63	0.52	0.89	0.42	0.49	0.69	0.62
2000	0.67	0.71	0.59	0.57	0.75	0.66	0.87	0.52
2500	0.44	0.39	0.49	0.63	0.87	0.94	0.74	0.76
10,000	0.72	0.74	0.87	0.65	0.56	0.89	0.92	0.56

4.2. Change in Current Density and Actual Inter-Electrode Voltage in Magnetic Polarized Water in PEM Electrolyzer

The quantified distilled water, treated by polarization in different magnetic fields, was put into the PEM electrolyzer. When the control power supply provides a constant current of 0.7 A, the fitted changing curve of the actual inter-electrode voltage of the electrolyzer is shown as curve (a) in Figure 8. It can be observed that, with continuous increases in the magnetic field's intensity, the actual inter-electrode voltage shows a decreasing trend, and the decrease rate continuously slows. The fitted changing curve of the electrolyzer electrode plate's current density when controlling the DC power supply to provide an 11 V constant voltage is shown as curve (b) in Figure 8. The figure shows that, with the increase in the magnetic field's intensity, the actual inter-electrode voltage shows an increase trend, and the increase rate continuously slows. The experimental phenomena show that, with pre-magnetic polarization treatment, the properties of distilled water are changed. The ionic diffusion coefficient in water increased, the resistivity of the electrolyte decreased, and the resistance potential was effectively reduced, thereby reducing the actual inter-electrode voltage of the electrolyzer.

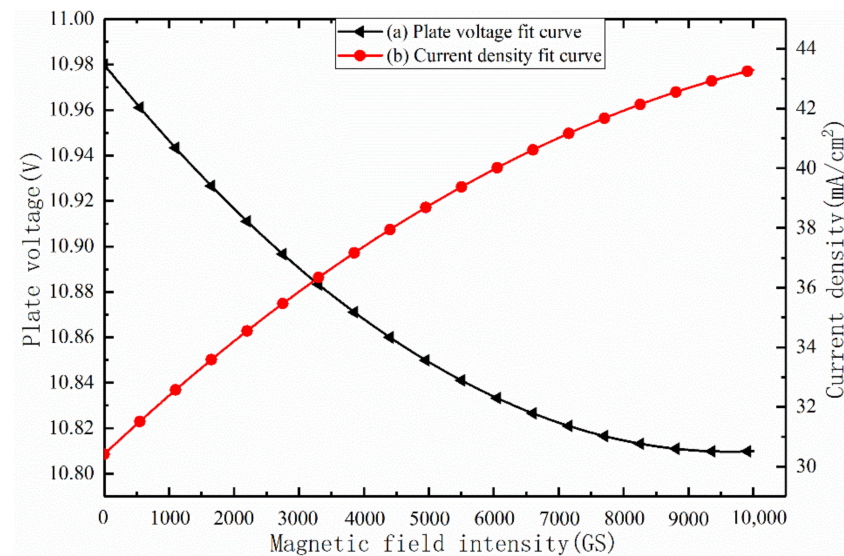


Figure 8. Fitting curves of inter-pole voltage and plate current density in PEM electrolyzer for hydrogen production by electrolysis of distilled water after different magnetic field treatments.

4.3. Hydrogen Production Rate and Energy Consumption

A total of 350 mL distilled water was taken, either without magnetic polarization treatment or with different magnetic field magnetic polarization treatments, and the sample was passed into the PEM electrolytic cell for hydrogen production experiment. Meanwhile, in different time periods, the changes in the hydrogen production of each sample were recorded by a high-speed camera in different time periods. Due to the electrolyzer's defects, only the changes in hydrogen production within 100 s were observed. In order to reduce the experimental error, the research group conducted a large number of repeated experiments. Figure 9 shows the time-variant hydrogen production of electrolyzing distilled water, which pre-polarization in different magnetic fields. It can be seen that the hydrogen production rate in the PEM electrolyzer significantly increased with pre-magnetic polarization treatment.

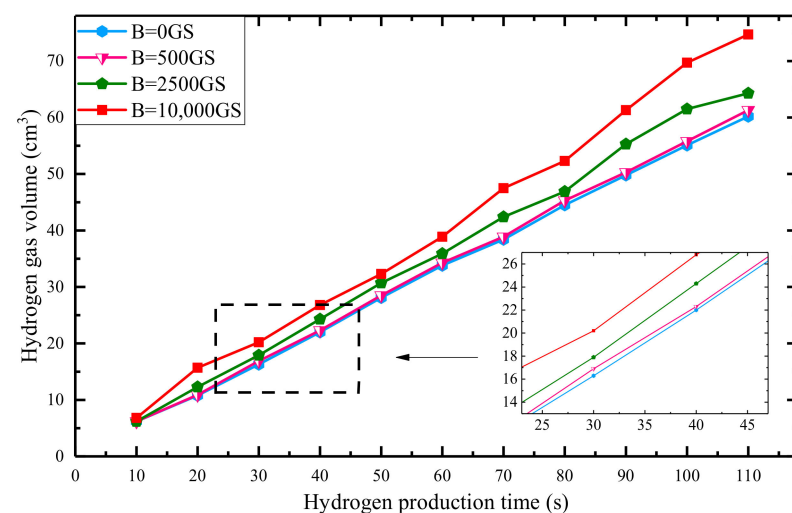


Figure 9. Variation in hydrogen production from distilled water with time after pre-polarization of different magnetic fields.

As shown in Table 2, it can be seen that the error between experimental data and expected value is less than 3%.

Table 2. The uncertainty of hydrogen production rate in these experiments.

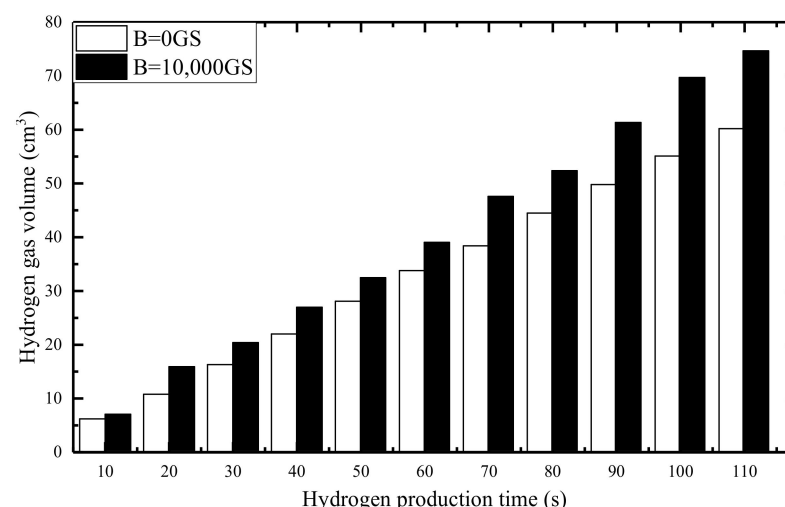
	Hydrogen Production Time (s)							
	10	20	40	60	80	90	100	110
Magnetic Field Intensity (GS)	Uncertainty of Hydrogen Volume (%)							
500	1.63	1.78	2.02	1.97	2.14	1.53	2.34	1.63
1000	1.52	1.38	2.21	2.03	1.69	2.54	1.14	1.83
1500	1.49	2.31	1.39	2.19	2.63	1.84	1.58	2.93
2000	1.69	1.47	1.76	2.63	3.04	2.93	2.79	1.73
2500	1.75	1.39	2.64	1.98	1.67	1.64	2.38	2.89
10,000	1.32	2.12	1.96	2.07	2.37	1.79	2.25	2.34

As shown in Table 3, the electric energy consumption needed to produce the same amount of hydrogen in the two experiments was calculated. This shows that, for the same amount of hydrogen production, the electric energy consumed by distilled water pretreated in 10,000 GS magnetic field was significantly reduced.

Table 3. Comparison of electric energy consumption needed to produce the same amount of hydrogen from distilled water without pre-magnetic polarization and with 10,000 gs magnetic polarization.

Hydrogen Volume (cm ³)	0 GS	10,000 GS
	Power Consumption (kW·h)	
10	0.04273	0.03148
20	0.08323	0.06091
40	0.15579	0.13242
60	0.23058	0.19961

As shown in Figure 10, the changes in hydrogen production between the two experiments were compared at different times, which indicates that the hydrogen production rate by distilled water pre-polarized by 10,000 GS magnetic field increased by 15–20%. At the same time, the energy consumption of hydrogen production by pre-magnetically polarized water was reduced, and its hydrogen production rate was improved. This verified the theoretical analysis in this work that, under the applied magnetic field, Lorentz force has a significant impact on the charge transfer in water electrolysis, and the relevant properties of water have been changed, making it easier to electrolyze.

**Figure 10.** Comparison of hydrogen production of distilled water without pre-polarization and after 10,000 GS magnetic field polarization.

5. Conclusions

Combined with the pre-magnetic polarization mechanism of hydrogen protons in electrolytes under a static magnetic field, this paper explored the molecular polarity and stress-strain characteristics of distilled water under pre-magnetic polarization. Additionally, a new hydrogen production method based on low-power and high-efficiency electrolysis under pre-magnetic polarization was proposed. By establishing the microscopic physical model of the energy-level transition of hydrogen protons in the magnetic field environment and the macroscopic mathematical model corresponding to the magnetization vector and the concentration of polarized hydrogen protons, both qualitative and quantitative analyses were carried out to study the ionic conductivity, electrolyte current density, interelectrode voltage, and hydrogen production under varying magnetic fields. The feasibility of the proposed method was verified by a water electrolysis hydrogen production experiment using a self-designed adjustable pre-magnetic polarization water electrolysis hydrogen production test platform. The test results show that the ionic conductivity of distilled water after pre-magnetic polarization treatment increased by 2–3 times. With the increasing magnetic field strength, the current density of PEM electrolysis continuously increases, while the voltage between electrodes continuously decreases and the hydrogen production rate significantly increases. When the magnetic field strength reaches 10,000 GS, the hydrogen production rate of electrolytic distilled water increases by 15–20% within a certain period of time.

The research described in this paper provides a theoretical basis for the parameter selection of hydrogen production using pulse current electrolysis. In future studies, a multiphysics numerical model for magnetized water will be developed, and pulse current techniques will be employed to further study.

Author Contributions: Conceptualization, K.L.; methodology, K.L. and H.Z.; validation, K.L., H.Z. and X.Z.; formal analysis, K.L.; investigation, H.Z. and X.Z.; resources, K.L. and C.L.; data curation, H.Z. and X.Z.; writing—original draft preparation, K.L. and H.Z.; writing—review and editing, K.L., C.L. and Q.C.; supervision, C.L.; project administration, Q.C.; funding acquisition, K.L. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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