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Hydrogen Energy: Hydrogen Production through Water Electrolysis Technology

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Abstract

Hydrogen energy, a highly efficient and clean alternative to fossil fuels, is produced via electrochemical water splitting through the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). However, OER's slow kinetics hinder efficiency. This article focuses on two technologies: proton exchange membrane (PEM) electrolysis and alkaline electrolysis. PEM electrolysis, using precious metal catalysts, offers high efficiency but at a high cost. In contrast, alkaline electrolysis employs cost-effective and mature nickel-based catalysts. Seawater electrolysis, abundant in resources, faces chloride competition and corrosion challenges, requiring highly selective OER catalysts. Transition metal-based materials show promise in both acidic and alkaline environments, offering cost reduction potential. Despite its immense potential for energy transition, further breakthroughs are needed to overcome technical barriers for large-scale application of electrochemical water splitting.

Keywords

Hydrogen; OER; Water-splitting.

1. Introduction

Currently, the greenhouse effect caused by fossil fuels necessitates an urgent search for sustainable energy sources. Hydrogen energy, with its high energy density, is increasingly recognized as an ideal energy source.[1-3] Additionally, the atmospheric pollution and greenhouse effect resulting from the use of fossil fuels have heightened the demand for clean energy. Hydrogen energy, characterized by its high mass energy density and renewability, is an ideal substitute for fossil fuels. Electrochemical water splitting is one of the most convenient, green, and sustainable methods for hydrogen production. Hydrogen energy has a high combustion heat value (1.4x10^8 J/kg), second only to nuclear energy, and its combustion produces only water, making the entire combustion process pollution-free and environmentally benign.[4] Considering the abundance of seawater on Earth (accounting for 96.5% of the world's total water volume), direct seawater electrolysis technology can help alleviate freshwater shortages, especially in arid regions.[5] The overall reaction of electrochemical water splitting can be divided into the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER). The slow kinetics of the oxygen evolution reaction (OER) at the anode, which involves a four-electron reaction step, is a bottleneck in the overall water splitting process. Therefore, designing and constructing efficient electrochemical OER catalysts is crucial for hydrogen production through water electrolysis.

1.1. Water Electrolysis

1.1.1. PEM Electrolysis

A Proton Exchange Membrane (PEM) electrolyzer, the core component of a Proton Exchange Membrane Water Electrolysis (PEMWE) system, utilizes a proton exchange membrane as the electrolyte to decompose water into hydrogen and oxygen under direct current. A standard PEM electrolyzer stack consists of multiple cells arranged between an anode and a cathode. Each cell includes a gas diffusion layer (GDL), separators for water distribution, and a membrane electrode assembly (MEA). The electrochemical reactions in a PEM electrolyzer can be summarized as follows[6]:

Overall:$H_2O \rightarrow H_2 + {}^1/_2\, O_2$

Anode:$H_2O + 2H^+ \rightarrow {}^1/_2\, O_2 + 2e^-$

Cathode:$2H^+ + 2e^- \rightarrow H_2$

The primary components of a PEM electrolyzer include the membrane electrode assembly (comprising the proton exchange membrane, catalyst layers, and gas diffusion layers), bipolar plates, end plates, and sealing components. These parts work together to enable efficient water electrolysis, producing hydrogen and oxygen while ensuring system integrity and stability. PEM electrolyzers typically operate at temperatures between 50–80 °C, with the optimal range depending on the specific catalyst and membrane materials used.[7] The efficiency and performance of the electrolyzer are influenced by factors such as reactant gas pressure and current density.[8]

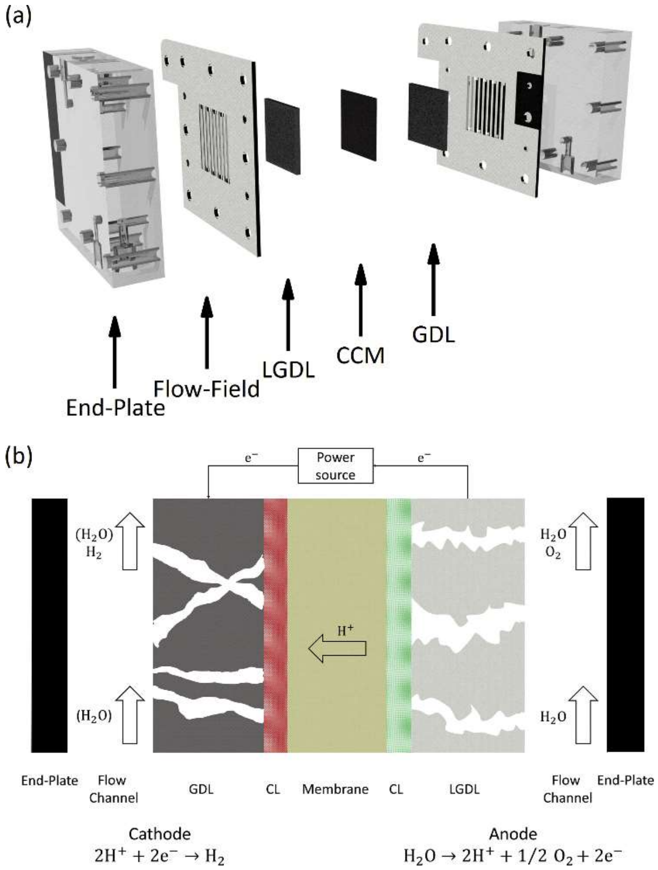

Fig. 1 (1) The assembly of a single-cell PEMWE with end-plates, flow-field, liquid-gas diffusion layer (LGDL), gas diffusion layer (GDL), and catalyst coated membrane (CCM). (2) Schematic of components and mass flows in a PEMWE.[9]

As shown in Fig. 1, a typical PEMWE assembly includes a catalyst-coated membrane (CCM), a liquid-gas diffusion layer (LGDL) at the anode, a gas diffusion layer (GDL) at the cathode, flow fields, and end plates. Gaskets (not shown in the figure) are used to secure the LGDL, GDL, and CCM in place and to prevent gas or liquid leakage.[9]

In PEMWE (Proton Exchange Membrane Water Electrolysis), both the oxygen evolution reaction (OER) at the anode and the hydrogen evolution reaction (HER) at the cathode require highly efficient catalysts to accelerate the reaction kinetics. Currently, iridium-based catalysts are the most commonly used OER catalysts in PEMWE, while platinum-based catalysts are employed for the HER. [10]However, the scarcity and high cost of iridium and platinum have driven researchers to explore alternative materials that are either non-precious metal-based or contain reduced amounts of precious metals.[11] For example, transition metal oxides, sulfides, and phosphides have demonstrated promising OER and HER catalytic activity in acidic environments. [12]These materials are not only cost-effective but also hold significant potential for future applications.

1.2. Alkaline Electrolysis

An alkaline electrolyzer is a device that utilizes an alkaline electrolyte (typically a solution of potassium hydroxide or sodium hydroxide) for hydrogen production through water electrolysis.[7] It is one of the most mature and widely used technologies for water electrolysis, offering advantages such as low cost, long lifespan, and well-established technical maturity.[6] The alkaline electrolyzer produces hydrogen and oxygen by decomposing water through the application of direct current. Its core principle relies on the use of an alkaline electrolyte to conduct ions and maintain the reaction environment. Alkaline electrolysis utilizes electrodes made of non-platinum group metals, such as nickel (Ni) and iron (Fe), along with a diaphragm membrane and a 30-40% potassium hydroxide (KOH) electrolyte solution.[13]

In alkaline electrolyzers, the choice of catalyst materials for both the OER and HER is more extensive. For instance, nickel-based catalysts, such as NiFe oxides[14], exhibit excellent OER activity under alkaline conditions, while nickel-molybdenum (NiMo)[15] or nickel-cobalt (NiCo) alloys are commonly used for the HER. In recent years, researchers have also developed a variety of transition metal-based composite materials and nanostructured catalysts. By tuning the electronic structure and surface properties of these materials, the catalytic performance has been further enhanced.[16]

1.3. Seawater Electrolysis

Currently, research on water electrolysis mainly focuses on the use of high-purity fresh water.[17] The abundant seawater resources on Earth, which are virtually inexhaustible, make direct seawater electrolysis for hydrogen production a technology of great significance.[18] However, seawater electrolysis faces challenges such as chloride ions (Cl^-) competing with the OER, triggering the chlorine evolution reaction (CER). [19]This reduces OER efficiency and may produce toxic chlorine gas. Thus, developing selective and corrosion-resistant OER catalysts is key to advancing seawater electrolysis.

2. Conclusion

Although electrocatalytic water splitting has made significant strides, challenges remain. Key areas include developing efficient, low-cost non-noble metal catalysts and enhancing catalyst stability in harsh conditions. Strategies like nanostructuring and element doping can further optimize catalyst performance. In summary, this green, sustainable hydrogen production method holds great potential and may soon enable large-scale, low-cost hydrogen generation, accelerating clean energy adoption.

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