

Structure and materials of alkaline fuel cell

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Abstract. To solve the problems of energy and environment, after experimentations and selections, hydrogen steps into the limelight; we call it "the ultimate energy source for the development of human society," and fuel cell technology is an essential step of pursuing the recyclable hydrogen energy. Fuel Cell is viewed as one of "The ideal power generation devices in the 21st century"; it has a high energy transformation efficiency, and the electricity generation process has a low environmental impact. If the fuel is being provided, fuel cells can continuously provide electricity, which can likely be applied in power plants, electric vehicles, electronic devices, mobile communications, and space facilities. This work focuses on Alkaline Fuel Cells. The oxidation-reduction process will be more straightforward in alkaline-based electrolytes than in acidic electrolytes, and the alkaline system will also perform better under room temperature. Besides, Alkaline Fuel Cells (AFC) can use non-platinum catalysts, so the cost is lower than the other Fuel Cells. Thus, designing a Hydrogen-based AFC is what's being focused on in this article. However, AFC has its disadvantages too. First, the CO₂ in air and fuel gas must be cleaned up because of the alkaline electrolyte. Furthermore, water is a by-product of the electrochemical reactions inside AFCs. Therefore, AFC performance will be seriously affected if the water doesn't expel. Another issue that current AFCs face is the problem of CO₂ poisoning. To address the above questions, we approached it from a thermodynamic perspective, compared the basic structure, material, drainage method, etc., of multiple alkaline fuel cells, and selected the more efficient ones that will be more effective for developing the AFCs.

Keywords: AFC, Electrode, Electrocatalyst.

1. The current research status and applications of AFCs

AFCs are efficient and eco-friendly electrochemical devices that have gained attention for their potential use in power generation, transportation, and portable electronic devices. Current research aims to improve AFCs' performance, durability, and cost-effectiveness by developing new materials like anion exchange membranes and non-noble metal catalysts and exploring methods to control operating conditions. However, developing high-performance materials that can withstand harsh conditions and reducing AFCs' costs are still challenges that need to be addressed [1].

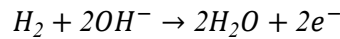
AFCs have been explored for various applications, including stationary power generation, transportation, and portable electronic devices. AFCs offer high efficiency, low environmental impact, and a longer lifespan than other types of fuel cells. For instance, NASA has used AFCs in space missions due to their high reliability and long lifespan [2]. In addition, AFCs have been tested in hybrid buses and electric vehicles due to their high-power density and fast response [3]. With continued research efforts, AFCs are expected to play a significant role in the transition to clean energy sources in various sectors.

2. The principle, structure, and materials of AFCs

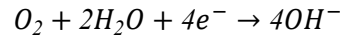
2.1. The principle

Alkaline Fuel Cells, in short AFC, is a fuel cell invented by Francis Thomas Bacon, which uses KOH Aqueous solution as electrolytes, carbon as the electrode, and potassium hydroxide as the electrolyte. The energy conversion efficiency of AFCs is the highest among all fuel cells, up to 70%.

The working principle of an AFC is that there are two fuel inlets for hydrogen and oxygen, respectively, which enter the cell through separate ports. In the middle is a porous graphite electrode, and the electrolyte is located in the center of the carbon cathode and carbon anode. Hydrogen gas enters the electrolyte through the porous carbon anode, and upon contact, it undergoes oxidation, producing water and electrons:



An external circuit provides the electron to generate electricity and flows back to the cathode, where it reacts with oxygen and water to form hydroxide ions:

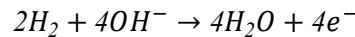


Finally, water vapor and heat leave the outlet, and hydroxide ions flow back to the anode through the potassium hydroxide electrolyte, completing the entire circuit.

The reaction principle of an AFC:

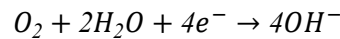
AFCs typically use potassium hydroxide or sodium hydroxide as the electrolyte, with the conducting ion being OH⁻ and the fuel being hydrogen.

Anode reaction:



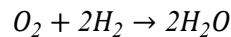
with a standard electrode potential of -0.0828V.

Cathode reaction:



with a standard electrode potential of 0.401V.

Overall reaction:



with a theoretical electromotive force of 0.401 - (-0.828) = -1.229V.

The catalysts for AFCs are mainly precious metals such as platinum, palladium, gold, and silver, as well as transition metals such as nickel, cobalt, and manganese.

2.2. Electrode structure

This section mainly introduces Double-hole structure and Adhesive type electrodes mixed with waterproof agents such as polytetrachloroethylene.

F.T.Bacon utilizes Raney alloy to develop a double-hole structure electrode; controlling the reaction ga and the electrolyte pressure differential allows the reaction area to be held in the coarse pore layer while the fuel cell works. A great way to increase the electrocatalytic activity of double-hole electrodes is to introduce high catalytic activity components into the rough pore layer of the dual pore electrode.

Function-wise, the fine pore layer of the double-hole electrode, when immersed in the electrolyte, acts as a gas barrier and conducts conductive ions. Therefore, microporous plastic can be used as a fine pore layer. However, the double-hole electrode only applies to Cryogenic Fuel Cells [4].

In aqueous solution electrolytes, some materials, such as activated carbon with various electrocatalysts, can be infiltrated and are good conductors of electricity. These materials can provide channels for electron conductivity and liquid mass transfer, yet, they can't provide a gas channel for transferring reaction gas. Due to its hydrophobic characteristic, other materials, such as PTFE durable water repellent, can create a gas channel if added. The addition of durable water-repellent allows the gas channel, has an adhesive effect and allows the dispersed electrocatalyst aggregates to be firmly bound.

PTFE's primary purpose in the electrode is to compose a hydrophobic grid to provide a passage for the reaction gas. However, PTFE is non-electric conductive; the high content of PTFE will cause a high electrical resistance and result in the increased loss of ohmic polarization; if there's a low content of PTFE, the gas transformation resistance will increase, and increase the concentration polarization loss of the electrode, which is shown very distinct when the electrodes are working under a high electric density. Therefore, for a particular electrode, there should be an optimal interval of PTFE content. Besides, the ratio of the hydrophilic network formed by the catalyst to the hydrophobic network created by PTFE within the electrode is essentially a volume ratio, so electrodes made of silver and platinum black as electrocatalysts. The mass fraction of PTFE within the electrode is generally 10% to 20% due to the high density of metal powder, while for electrodes prepared by Pt/C and other electrocatalysts, the mass fraction of PTFE within the electrode is generally between 30% and 50% due to the low density of Pt/C catalyst [5].

2.3. *Electrocatalyst*

From the elemental composition, the electrocatalysts of AFCs are mainly noble metals and transition metals, noble metals and noble metals, or noble metals and transition alloys.

Since the anode catalyst in AFCs is easily poisoned by the intermediate products, such as CO, produced by the oxidation reaction occurring in the fuel, catalytically active and stable catalysts are required.

In AFCs, alloy catalysts are prepared by doping with one or two metals, metal oxides or non-metals, to exploit the synergistic effect of different elements and improve the utilization rate of metals and the electrocatalytic activity and stability of fuel cell anode catalysts; by changing the preparation method of alloy catalysts, the loading and dispersion of stimuli on the carrier can be improved. Alloy catalysts are divided into metal-doped alloy catalysts, metal oxide-modified alloy catalysts, and non-metal-modified alloy catalysts. In the study of metal-doped alloy catalysts, Brouzgou et al. synthesized three catalysts, Pd Sn/C, Pd₃Sn₂/C, and Pd/C, by a modified pulsed microwave-assisted polyol method, and examined their reactions for glucose electrooxidation in alkaline media, as well as the effect of electrolyte and glucose concentrations on catalyst activity, and observed that an increase in electrolyte and glucose concentrations [6]. It was observed that the addition of electrolyte and glucose concentration could increase the rate of glucose electrooxidation. Their study showed that Au and Sn were added to enhance the catalyst activity in an alkaline medium. Mukherjee et al. synthesized Pd-Cu alloy nanoparticle catalysts with different ratios of Pd and Cu in a robust alkaline solution at room temperature using the metal co-reduction method. They analyzed them through a series of processes. They found that Pd_x1-x/C (x:1-x is x=0.50-0.95) catalysts were catalytically active for ethanol oxidation in an alkaline medium [7]. Among them, the Pd_{0.90}Cu_{0.10}/C catalyst showed the best catalytic activity in EOR, greater acetaldehyde oxidation capacity, and the highest exchange current density in EOR than the Pd/C catalyst.

In the study of metal oxide-modified alloy catalysts, nano metal oxides (Ti O₂, Ce O₂, etc.) have better chemical stability and corrosion resistance and exhibit catalytic enhancement, strong interaction, and overflow effect between them and metal catalysts [5]. Then Pd-Mo O₂-C and Vulcan XC-72 carbon powder were used in a 1:1 mass ratio to make the anode catalyst for the Pd-Mo O₂/C ethanol fuel cell. Their study showed that the Pd-Mo O₂/C electrode has excellent electrocatalytic activity for ethanol oxidation under alkaline conditions, and the catalytic activity is relatively stable [8].

Jiang et al. prepared Pd-Ni-P electrocatalysts for EOR with a smaller particle size amorphous structure than Pd-Ni samples without P and control Pd black (Pd-blk) samples. The Pd-Ni-P catalyst has more active electrocatalytic sites in alkaline media than the Pd-Ni and Pd-blk catalysts. For EOR in 0.1 mol/L KOH, the Pd-Ni-P catalyst has a more significant negative onset potential, the most negative peak potential, and the highest catalytic current [9].

2.4. Anion exchange membranes

Anion-exchange membrane fuel cells (AEMFCs) have received attention from researchers for their application in AFCs because they have more advantages than other types of fuel cells, such as higher reaction efficiency for the reduction of oxygen under alkaline conditions, allowing the use of non-precious metals such as Ag, Co, and Ni as catalysts, and better tolerance to carbon monoxide in gas feedstocks [10].

Anion exchange membranes (AEMs) have a crucial function in fuel cells. In AEMFCs, the central role played by anion exchange membranes is to isolate the anode from the cathode and conduct hydroxide ions [11]. To meet the performance requirements of AEMFCs, anion exchange membranes need to have the following properties:

- Anion exchange membranes should have mechanical solid and thermodynamic stability properties;
- They should be able to conduct hydroxide ions and have high hydroxide ion conductivity;
- They should have high alkali stability properties;
- To reduce fuel permeation, anion exchange membranes need to have good densification and swelling resistance;
- Low cost.

However, the hydroxide ion conductivity of anion exchange membranes is lower than the proton conductivity of proton exchange membranes because the backbone structure of ionic polymers and cation exchange groups are prone to degradation under alkaline conditions and the mobility of hydroxide ions is lower than the mobility of protons.

According to the different backbone structures of polymers, anion exchange membranes are classified into polyphenylene ether-based anion exchange membranes (PPO), polyaryl ether sulfone anion exchange membranes, polyolefin anion exchange membranes, polybenzimidazole-based (PBI) anion exchange membranes, and other polymer-based anion exchange membranes.

Anion exchange membranes are the critical components of AEMFCs, acting as ion conductors and fuel barriers, and their properties determine the performance, energy efficiency, and lifetime of AFCs.

Although researchers have extensively studied the preparation and performance of anion-exchange membranes with polymer backbone structure and made some progress, the research on anion-exchange membranes still needs to be considerably deepened. Feng-Yan Fu et al. proposed that the degradation mechanism of anion-exchange membranes can be studied to improve the alkali stability performance of the membranes; new functional groups can be designed based on the existing polymer backbone to enhance the study of the effect of anion-exchange membranes on battery performance, etc [12].

2.5. Drainage System

The product water produced by the fuel cell process must be continuously drained from the cell stack to keep the concentration of KOH within a specific range. Depending on the electrode type, there are different ways to drain the water accordingly.

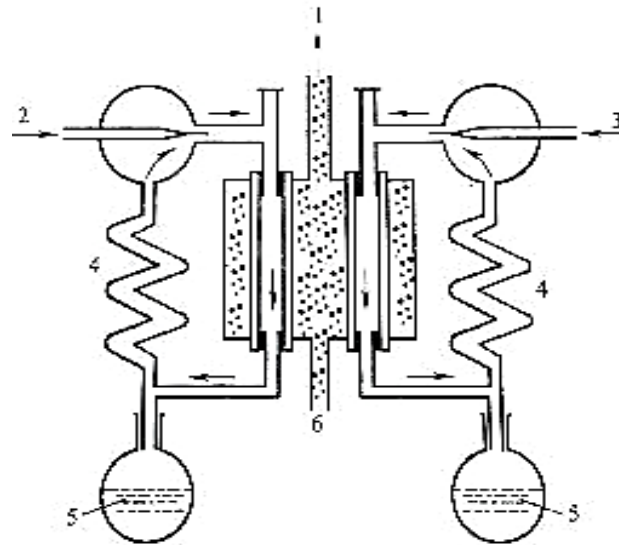


Figure 1. Schematic diagram of jet double cycle water removal system. 1-Circulating electrolyte. 2-High pressure hydrogen. 3-High pressure oxygen. 4-Condenser. 5-Water tank. 6-KOH electrolyte.

One type carries the water in a circulating electrolyte. It cools the stack, with evaporation occurring outside the stack, as in the case of Siemens' H₂-O₂AFC, and the other type removes the water through a reaction gas cycle. Figure 1 is a gas jet dual-cycle water removal system schematic diagram. The system has a gas injector and a condenser. The injector injects high-velocity gas in a specific ratio according to the consumption of the reaction gas at the electrode to produce a gas stream, and the gas stream flowing out of the electrode removes water through the condenser. The remaining reaction gas continues to circulate. The water removal efficiency of the anode is higher than that of the cathode. Because AFC generates water at the anode, the electrolyte concentration at the anode is lower than the concentration of the body, and the vapor pressure is higher. While the cathode reaction consumes water, the electrolyte is concentrated in the cathode, and the vapor pressure is lower.

2.6. Waste heat cooling

In a hydrogen-oxygen AFC, whether of the Electrochemical Energy Corporation or the Siemens type, the residual heat is considerable if a circulating electrolyte is used. Electrochemical Energy has two heat removal paths for hydrogen-air AFC: air and electrolyte. In both AFCs, the electrolyte must pass through a heat exchanger. If the electrolyte is fixed, as in the case of fuel cells used on U.S. spacecraft, a unique cooling system must be installed after each interval of a certain number of cells (groups) to remove the residual heat from the cell stack.

3. Battery System Life of AFC system

The lifetime of a fuel cell is a balance of technical and economic lifetime. The economic life depends on the application area of the battery; some areas only need 5000 hours or even 1000 hours of life, some need 25000 hours or even longer, and power plants need at least 40,000 hours of life. The technical life of the battery stack is mainly affected by the stability of the catalyst and its performance. There are still many areas to be optimized in this regard. Hydrogen-oxygen and hydrogen-air AFC battery stacks typically have a lifetime of 5000 hours with a voltage drop of 20mV or less per thousand hours. The average life of AFC used in U.S. human-crewed spacecraft is 2000 hours, and the life of 20 sets of 6kW AFC systems produced by Siemens in Germany can reach 8000 hours.

4. Conclusion

For the electrode, the double-hole structure electrode is only suitable for low-temperature fuel cells, and the bonded electrode adulterated with a water-repellent such as poly(tetrachloroethylene) should be selected with a suitable PTFE content range. For the anion exchange membrane, there is still a lot of room for improvement, especially in improving the alkali stability of the membrane. For the drainage method, the circulating electrolyte carries the water and cools the cell stack. The evaporation of water is carried out outside the cell stack, or the water is removed by the reaction gas cycle, depending on the situation.

In this paper, we study in detail some of the structures and drainage methods, waste heat cooling, and other aspects of AFCs, summarize the current development status, compare them, put forward the focus of attention and solutions, and hope to provide a reference for the recent research of AFCs.

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