An Efficiency Consideration for the Hydrogen Fuel Cell: A Technical Evaluation

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Introduction

There are four aspects of today's power supplies that are under heavy scrutiny by the entire world: cleanliness, renewability, reliability, and yield. Humanity began primarily relying on fossil fuels for power on a significant scale in the mid-18th century. However, fossil fuels produce greenhouse gas emissions, which were initially passed off as inconsequential but have begun to pose a serious threat as their finitude and emissions become more pronounced. Consequently, the world is pursuing clean and renewable energy. Hydrogen fuel cell technology is an alternative clean energy solution with low density, high combustion energy, and zero pollutant emissions (Felseghi et al., 2019). Additionally, unlike wind and solar, its output is stable (Gaster, 2024). It meets three of the four criteria we have preliminarily put forth; it is clean, renewable, and reliable. However, its current conversion efficiency is low and incapable of meeting our increasing energy needs on a global scale. We must then address the two primary factors limiting the ability of hydrogen fuel cells (HFCs): high manufacturing costs and low energy yield. Although HFCs may never produce as much energy as nuclear or fossil fuels, they can be optimised with low-cost materials that minimize energy loss.

Into the Hydrogen Cell

All fuel cells are composed of an anode, a cathode, and an electrolyte membrane. A fuel cell generates electricity via an electrochemical (redox) reaction. In HFCs, hydrogen and oxygen react to produce water vapor and heat, wherein hydrogen is oxidized at the anode and oxygen is reduced at the cathode (Tuan et al., 2018).

Hydrogen gas (H_2) is supplied to the anode of the fuel cell, where a catalyst splits the H_2 molecules into protons (H+) and electrons (e-) (Huang et al., 2006):

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

Next, proton conduction in the electrolyte layer occurs. The protons generated at the anode must reach the cathode but cannot travel through the external circuit directly. Instead, they pass through a proton exchange membrane (PEM), which is a solid polymer electrolyte that permits only protons to pass through while blocking electrons (Larminie et al., 2003). Meanwhile, the electrons travel through an external circuit to the cathode. This flow of electrons through the circuit generates an electric current, which we harness as electricity. On the cathode end, Oxygen gas (O_2) is provided. There, the protons and electrons arrive to combine with O_2 to form water (Felseghi et al., 2019):

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow 2H_2O + \text{electricity} + \text{heat}$$

Identifying Design Challenges

The total energy released in any physical or chemical reaction is a fixed quantity that cannot be manipulated. Thus, efficiency is measured by how closely the actual yield approaches the theoretical yield, though 100% efficiency is unattainable. Current HFCs run from about 40% to 60% electric efficiency (Giddey et al., 2012). However, this percent can be optimized by minimizing energy losses. One strategy for achieving this includes adjusting temperature and pressure conditions of the fuel cell to enhance collision rate at the electrode and proton conduction at the PEM (Cheng et al., 2007). In addition, the energy needed to facilitate the reaction (activation energy, E_a) can be reduced through catalysis, which provides an alternative pathway with a lower E_a.

Temperature and Pressure to Expedite Proton Conduction

The reaction rate of $H_2(g) + ½ O_2(g) \rightarrow H_2O(g)$ without a catalyst is considered negligible at room temperature, due to its high activation energy barrier. One approach to trigger a rapid reaction is by providing the necessary activation energy in the form of thermal energy through a spark or heat source. Another strategy is precisely controlling the pressure of the cell (Cheng et al., 2007). In the study *Hydrogen crossover in high-temperature PEM fuel cells*, published in 2007 in the *Journal of Power Sources*, researchers measured how much hydrogen passes through the PEM under different ranges of conditions, such as temperature (80-120ºC), pressure (1-3 atm), and humidity (25-100%). They discovered that increasing temperature and pressure generally makes it easier for hydrogen to cross the membrane, increasing the HFC's efficiency, while humidity hampers it. This is supported by Collision Theory, which states that both increased temperature and pressure heighten the rate of collision between gas molecules, augmenting the overall rate of reaction.

Electrocatalyst Performance Enhancement

However, operating at high temperatures and pressures risks degradation of fuel cell components through thermal decomposition or physical damage (Shao et al., 2007). Thus, research prioritizes improving catalyst design, which has a higher impact on cost and energy efficiency (Adams & Chen, 2011). As mentioned earlier, one shortcoming of the HFC is its high manufacturing cost, mainly due to the catalyst material, which is typically platinum (Pt) or a Pt group element. Many studies propose palladium (Pd) as a replacement electrocatalyst. Like Pt, Pd adsorbs H_2 and separates the molecules into electrons and protons via hydrogen oxidation reaction (HOR), lowering E_a. It also catalyzes oxygen reduction reactions (ORR). Pd offers advantages because it is less expensive, over fifty times more abundant than Pt, and highly resistant to corrosion and oxidation (Antolini, 2009). Currently, platinum is the most commonly used catalyst in HFCs due to its high catalytic activity and stability (Samris et al., 2021). While palladium is similar to platinum, its performance is often lower, making it less ideal for fuel cell applications (Schwartz, 1971). Some studies focus on minimizing corrosion from side reactions between the electrolyte membrane and the catalyst, which would improve fuel cell longevity and efficiency. Fuel cell corrosion and longevity is addressed in studies evaluating the acidic environment within proton exchange membrane fuel cells (PEMFCs). PEMFCs use highly acidic electrolytes such as sulfuric acid, formic acid, or Nafion ($pH < 1$) to facilitate proton conduction. One study found that "Pd-based materials have shown higher catalytic activity than Pt-based ones for some reactions…in acidic solutions. [However] The catalytic activity and stability of pure Pd are not high enough to replace Pt in fuel cells" (Zhang et al., 2016). In other words, Pd resists corrosion better than Pt in acidic PEM environments, however, in its pure form, it is inferior to Pt. Research is ongoing in ways to enhance the performance of palladium by alloying it with other metals to improve its catalytic activity and stability in fuel cells. According to Ermete Antolini, "The activity for the oxygen reduction reaction (ORR) of Pd is only slightly lower than that of Pt, and by addition of a suitable metal, such as Co or Fe, the ORR activity of Pd can overcome that of Pt. Conversely, the activity for the hydrogen oxidation reaction (HOR) of Pd is considerably lower than that of Pt, but by adding of a very small amount (5 at%) of Pt, the HOR activity of Pd attains that of pure Pt" (Antolini, 2009). Thus, alloying Pd can enhance its performance beyond Pt in some cases. Moreover, the catalyst's active site (where reactions occur) can be designed for precision and efficiency, minimizing side reactions and increasing activity by using single-atom catalysts or nanomaterials with large surface areas (Shah et al., 2022). As seen, Pd can be a transforming factor in optimizing the HFC's yield and increasing its performance in the energy market.

Conclusion

The HFC runs on an electrochemical combustion reaction with lower enthalpy than fossil fuel combustion but still high energy output. Since this is fixed, optimization is limited to focusing on improving efficiency and reducing cost. However, these objectives often conflict. To improve efficiency, better materials are needed, but they can be more expensive, increasing costs. Likewise, cheaper materials lower costs but may reduce efficiency. Research suggests that the best middle ground is substituting platinum for palladium for similar efficiency at lower cost, and using a corrosion-resistant proton conductor to extend fuel cell longevity. Additionally, operating at higher temperatures and pressures can speed up proton conduction and enhance reaction rates. Since hydrogen combustion yields less energy than fossil fuels, it is unlikely to overtake them in the market. However, with technical and economical improvements, HFCs could, at least, achieve commercial success.

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