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Regarding the Hybrid Fuel Cell: On a Design Interlinking and Gaining the Most From Microbial and Hydrogen-Powered Fuel Cells

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Abstract

As renewable-energy technologies are garnering much attention due to the necessary mitigation of climate change, the requirement for a fuel cell utilizing a clean source of dihydrogen input appears to be of the utmost importance. The following work hypothesizes a hybrid fuel cell utilizing both microbial and technological means for clean in-situ hydrogen production and subsequent energy production at potentially higher rates than standardized microbial fuel cells and with a negative carbon footprint.

Fuel cell technologies are of major interest in modern society [1]. With the ever-growing need for renewable and reliable energy-producing technologies, fuel cells are looked upon eagerly as a necessity for a carbon-free future. However, fuel cells operate on hydrogen, which is a resource that is neither environmentally friendly nor incredibly commercially viable [2].

Various microorganisms possess the ability to fix atmospheric nitrogen into ammonia or ammonium—hydrogen-carrying compounds—through the nitrogenase enzyme (eq. 1.1 and 1.2) [3, 4], and among these such organisms are cyanobacteria, algae that can thrive in low-nutrient environments due to their photosynthetic properties [5]. Among cyanobacteria, there exist two species that contribute the most to not only nitrogen fixation but direct hydrogen production in marine ecosystems [6], these two being the species Trichodesmium sp. erythraeum and Cyanothece sp. 51142.

\[
\begin{align*}
N_2 + 8H^+ + 8e^- + 16MgATP & \rightarrow 2NH_3 + H_2 + 16MgADP + 16P_i \\
\text{Equation 1.1} \\
N_2 + 14H^+ + 12e^- + 40MgATP & \rightarrow 2NH_4^+ + 3H_2 + 40MgADP + 40P_i \\
\text{Equation 1.2}
\end{align*}
\]

Therefore, in this paper, a version of the fuel cell, dubbed the hybrid fuel cell (HFC) for its utilization of microbial materials in conjunction with basic fuel cell materials, that utilizes the natural production of ammonium/ammonia in combination with organically produced hydrogen as a by-product of nitrogen-fixation as a source for hydrogen fuel is theorized. This version of the fuel cell will operate via atmospherically available molecules and sunlight in coordination with dihydrogen input, presenting the potential for the unification of both microbial and hydrogen-gas fuel cells through in-situ ammonium/ammonia production.

1 Results

1.1 Overview

The generation of electricity in the cell begins with the adequate filtration of dust and other microorganisms from the atmosphere and the allowance of light, carbon dioxide, and nitrogen into the cell, where this process is facilitated by the use of a membrane. After the initial separation, the microorganisms present will utilize the sunlight and carbon dioxide to perform photosynthesis and make energy (glycogen) for nitrogen fixation. It is during this time that the Trichodesmium colony will perform
nitrogen fixation and excrete ammonium and hydrogen while the Cyanothece colony will gather glycogen in its heterocysts to perform this process during nighttime. The ammonium produced by either Trichodesmium or Cyanothece will then venture through a cation-exchange membrane into a high pH (alkaline) solution (pH ≥ 10) via diffusion-dialysis [7], where it will turn into ammonia in an attempt to exercise equilibrium (eq.2), while the bio-hydrogen produced by the two species will be separated via the use of a gas-permeable hydrophobic membrane and directed towards the host fuel cell. The newly formed ammonia present in the high pH solution will then be separated from the solution via the use of a gas-permeable hydrophobic membrane [8] where it will venture to a specialized catalyst to be decomposed into hydrogen and appropriately filtered to the host fuel cell as fuel.

\[
\text{NH}_3 + \text{H}_2\text{O} \rightleftharpoons \text{NH}_4^+ + \text{OH}^-
\]

Equation 2.

1.2 Analysis of Membrane Filtration Technologies

Because the certainty that no external energy from the user is required is of the utmost importance and significance, membrane technologies must be a necessary requirement for the HFC to function conveniently [9, 10]. Multiple variations of membrane filters will be used, however, these variations never deviate from the nano-filtration and micro-filtration archetype with the exception of the cation-exchange membrane.

At least one dust and microbial filter should be utilized outside of the chamber containing the microorganisms, this filter should especially prevent hydrogen gas from escaping the water through volatilization as in the case of a hydrogen permeation barrier [11], as failure to do so will result in a loss of energy density. In the chamber housing the microorganisms, two filters equally divided should be used to selectively filter both ammonium and hydrogen gas from the water. The hydrogen-allowing filter should be hydrophobic and the ammonium filter should be a cation-exchange membrane. In the chamber housing the highly alkaline water, a hydrophobic hydrogen-allowing membrane equivalent to that of the microorganism chamber should be used. Finally, another hydrogen-allowing filter should be used in the chamber housing the catalyst for ammonia dissociation, and a gas-permeable water vapor filter should be used to filter the water vapor created from the reaction at the cathode to the microorganism chamber for reuse.

1.3 Analysis of Microbial Activity

Trichodesmium is widely recognized for its adept ability to perform nitrogen fixation and is regarded as the highest producer of fixed nitrogen in marine ecosystems [12]. As such, the use of Trichodesmium colonies in the scenario of a hybrid fuel cell appears favorable over others of its kind. The nitrogenase activity of Trichodesmium during appropriate culturing is relatively high compared to other species of
Figure 2: Comparison of the energy production of Trichodesmium compared to Cyanothece. Approximate functions for modeling the change in wattage over time equate to
\[ f(x) = -0.01(x - 14) + 0.2858 \]
where \( 20 \geq x \geq 8 \) for Trichodesmium e. colonies and
\[ f(x) = -0.03(x - 5) + 55731 \]
for Cyanothece colonies where \( 10 \geq x \geq 0 \) to represent the 10 hours that Cyanothece’s nitrogenase enzyme is active for.

cyanobacteria during natural culturing conditions, with cultures possessing an ammonium excretion rate of 729 \( \text{nmolNH}_4 \text{ mg}^{-1} \text{ H}^{-1} \) (measured in milligrams of chlorophyll a) [13] and a hydrogen excretion rate of 3 \( \mu\text{molH}_2 \text{ mg}^{-1} \text{ H}^{-1} \) [14]. It is due to the fact that the fuel cell can exploit both the production of ammonium and the production of hydrogen that the estimated electrical energy of the machine must be calculated with a combination of the two in mind, thus forming what will be called throughout the paper as the Total Hydrogen Potential (TPH) of the species. Thus, the total TPH of the species equates to 3.729 \( \mu\text{molH}_2 \text{ mg}^{-1} \text{ H}^{-1} \), and thus the ideal wattage (energy calculated disregarding energy loss as entropy change and energy losses associated with the procedures of the host fuel cell stack) equates to 0.2858\( \text{mW mg}^{-1} \) (milligrams of chlorophyll a).

Inconveniently, Trichodesmium cannot perform nitrogen fixation during the night and thus poses a weakness when presented as the lone contributor to the proposed hybrid fuel cell. Therefore, the use of Cyanothece as an assisting microorganism presents increasingly favorable outcomes. Despite Trichodesmium being considered to have greater nitrogenase activity than Cyanothece, the results mentioned above pale greatly in comparison to laboratory-grown, glycogen-nitrate-supported cyanobacteria [15, 16], with these cultures of cyanobacteria possessing a THP of 7.02 \( \mu\text{molH}_2 \text{ mg}^{-1} \text{ H}^{-1} \) (dry weight) [17, 18] assuming that the order of ammonium released is twice the amount of hydrogen released (eq. 1.1), several times higher than Trichodesmium even when the TPH of Trichodesmium is measured through the order of milligrams of chlorophyll. Based on the total hydrogen potential, the ideal wattage produced by the fuel cell during nighttime equates to 0.55731\( \text{mW mg}^{-1} \) (dry weight).

Additionally, nitrogenase activity is known to vary throughout the day, or rather throughout the night for Cyanothece, in accordance with the diel cycle. Ammonium—and subsequently hydrogen—production is known to peak midday for Trichodesmium and a few hours after midnight for Cyanothece cultures as shown in Figure 2.

Thus, the energy produced by the fuel cell varies throughout the day or night along with a two-hour gap between 20:00 and 22:00, and these variations must be taken into account during practical utilization either in the form of pairing the technology with other solutions or the temporary use of a battery for energy storage.
1.4 Analysis of the Ammonia Dissociation Catalyst

According to a study performed in 2017 by Katsutoshi Nagaoka et al., an acidic RuO2/γ-Al2O3 catalyst can be used for the room-temperature dissociation of ammonia into hydrogen and nitrogen [19]. This process presents extremely high rates of conversion—so grand that they can be effectively ignored—and is facilitated by oxygen. Thus, oxygen-allowing-hydrogen-disallowing and nitrogen-allowing-hydrogen-disallowing filtration should be used in the chamber where this process is occurring, as discussed above.

1.5 Fate of the Produced Hydrogen and Water Recycling

After all the novel processes of the HFC, the hydrogen produced will go towards powering a fuel cell stack, for which it can provide energy through the exothermic reaction between hydrogen and oxygen, forming water vapor. Under proper design, this production of water vapor from the fuel cell stack can be exploited to go back toward the microorganism chamber through diffusion, creating a complete hydrogen cycle under ideal conditions.

2 Discussion

The theoretical machine proposed in this paper presents many contributions to modern fuel cell technologies if proven empirically viable. It will do so through its flexibility of energy generation, being able to both take in hydrogen from the user and produce its hydrogen through the present cyanobacteria, as well as being more environmentally beneficial due to less emphasis exerted on external hydrogen input. Additionally, its creation of energy throughout nearly the entirety of the die cycle and moderate microbial efficiency (8-10% maximum) [20, 21] makes it an asset when used alongside modern photovoltaic systems, presenting less reliability on solar batteries for energy demand during the night.

Further areas of research and development of the HFC should primarily consist of more economically viable alternatives for the materials present in the fuel cell, as the use of multiple types of specialized membranes, catalysts, and bacteria causes the solution to be more costly at the expense of nearly unparalleled environmental friendliness. Additionally, Trichodesmium erythraeum and Cyanothece 51142 should be increasingly investigated for the estimated amount of maximum density these cultures can occupy in a milliliter of solution to predict the amount of space that can be conserved and the amount of water needed to produce certain energy densities. Further, these two species of bacteria should be investigated for electrogenic and photocurrent activities, as the addition of systems to harness these abilities would increase energy density and decrease energy loss throughout the system, providing an increasingly higher efficiency.

3 Methods

3.1 Analysis of Literature

During the research process, literature was carefully analyzed for rates of hydrogen production from various microorganisms. In the choosing of Trichodesmium e. and Cyanothece 51142 as the most probable candidates for microbial hydrogen production, various literature regarding the two organisms was further analyzed. After analysis of the various works and data, the data from the two papers claiming to have acquired the most hydrogen and ammonium production from the two species were taken into account for the research performed in this paper. Additionally, literature on wastewater treatment processes and membrane filtration processes were also analyzed for contributing information and conflicting information.

3.2 Calculations and Graphing of Mathematical Formulae

Wattage calculations were performed on the assumption that the average exothermic energy produced from the formation of water vapor through the combination of hydrogen and oxygen is 285.8 kJ and under the assumption that all of the dihydrogen and ammonium output produced by the microorganisms in a second will contribute to energy production. The mathematical functions representing the
average energy production of Trichodesmium e. and Cyanothece 51142 throughout various times of the day were graphed using MATLAB.

4 References


