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Floating membraneless PV-electrolyzer based on buoyancy-driven product separation

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ABSTRACT

This paper describes the design and performance of a scalable, stand-alone photovoltaic (PV) electrolysis device used for hydrogen (H_2) production by solar-driven water electrolysis. The electrolyzer component of this device is based on a simple, membraneless design that enables efficient operation with high product purity and without active pumping of the electrolyte. Key to the operation of this PV-electrolyzer is a novel electrode configuration comprised of mesh flow-through electrodes that are coated with catalyst on only one side. These asymmetric electrodes promote the evolution of gaseous H_2 and O_2 products on the outer surfaces of the electrodes, followed by buoyancy-driven separation of the detached bubbles into separate overhead collection chambers. The successful demonstration of this concept was verified with high-speed video and analysis of product gas composition with gas chromatography. While the device based on asymmetric electrodes achieved product cross-over rates as low as 1%, a control device based on mesh electrodes that were coated on both sides with catalyst had cross-over rates typically exceeding 7%. The asymmetric electrode configuration was then incorporated into a standalone, floating PV-electrolyzer and shown to achieve a solar-to-hydrogen efficiency of 5.3% for 1 sun illumination intensity. The simplicity of this membraneless prototype, as characterized by the lack of a membrane, scaffolding, or actively pumped electrolyte, makes it attractive for low-cost production of hydrogen.

Introduction

Hydrogen is an attractive carbon-free energy carrier that can be sustainably produced by water electrolysis if the electricity is provided by a renewable energy source. The commercial market for electrolyzers that are used to drive water electrolysis are currently dominated by two technologies: polymer electrolyte membrane (PEM) electrolyzers [1] and alkaline electrolyzers [2]. In both technologies, a membrane or diaphragm is positioned between hydrogen (H_2) and oxygen (O_2) evolving electrodes and serves a crucial role in device operation by separating product gases while enabling efficient transport of ions between the electrodes. However, membranes can be costly, prone to degradation and failure, and susceptible to cross-over issues [3]. An electrolyzer design that is able to operate with similar energy and collection efficiencies as the conventional technology but without a membrane is highly attractive [4–7].

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While membrane-free electrolysis has the potential to reduce the capital costs of the electrolyzer, its integration with a renewable energy source must be carefully considered in order for carbon-free H_2 generation from water electrolysis to become commercially viable. In the case of photovoltaic (PV)-electrolysis, integration of PV-cells with the electrolysis cells in a single device offers an opportunity to reduce the complexity and cost of the system [8–17]. The current study is motivated by the idea of incorporating PV-electrolysis reactors into a large-scale solar-hydrogen plant that operates on open water where sunlight, water, and non-agricultural space are extremely abundant. Such "solar fuels rigs" might be reminiscent, in some respects, to "deep sea rigs" used to harvest fossil fuels today [18]. Fig. 1a shows an idealized rendering of a floating solar fuels rig, where PV panels extending from the rig are integrated with low-cost membraneless electrolysis cells, which utilize the solar-generated electricity to split water into oxygen and hydrogen. Although seawater is cheap and abundant, there are substantial barriers to utilizing commercially available, membrane-based electrolyzers for H_2 production from seawater electrolysis. Microorganisms in seawater can lead to biofouling [19], and trace amounts of magnesium and calcium ions can form hydroxides that clog the pores of the membrane and increase cell resistance [20]. In contrast to conventional membrane-based electrolyzers, a membraneless electrolyzer is expected to have less stringent requirements for electrolyte purity, and thus may be uniquely suited for seawater electrolysis.

In the current study, we describe and demonstrate a prototype membraneless PV-electrolyzer design (Fig. 1b and c)

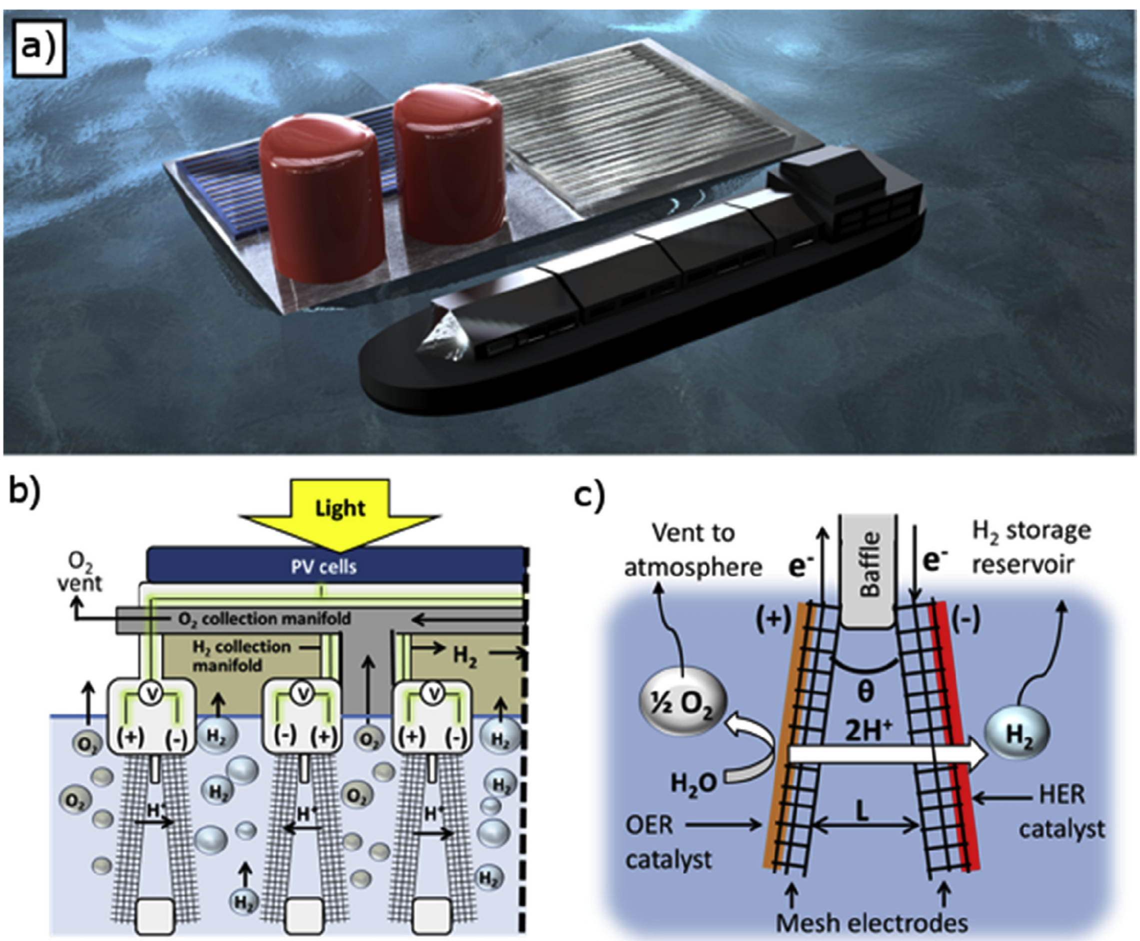

Fig. 1 – (a) Schematic of a deep sea "Solar Fuels Rig" based on a utility-scale, floating photovoltaic (PV)-electrolysis platform which uses sunlight to generate the solar fuel, H_2. On this rig, PV arrays mounted on a floating platform harvest sunlight and produce electricity that is sent to durable membraneless electrolyzers that split water into O_2 and H_2. Hydrogen generated by the electrolyzers is collected and stored in tanks above the surface where they wait to be shipped back to shore. (b) Schematic of novel membraneless electrode assemblies that are the basis of the current study and might one day be key components of the solar fuels rig. Alternating sets of membraneless electrolyzers wired in parallel use electricity supplied from the PV cells to split water into H_2 and O_2. (c) Close up schematic of a passive membraneless electrolyzer employing buoyancy-based product separation. The mesh electrodes are oriented at an angle θ, resulting in an average separation distance L. The electrocatalyst is deposited on the outward facing sides of the mesh in order to constrain product gas nucleation and growth to this region only. When the gas bubbles become large enough to detach, they float directly upward for collection or venting to the atmosphere.

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