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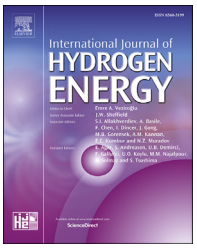

Performance evaluation of a photoelectrochemical hydrogen production reactor under concentrated and non-concentrated sunlight conditions

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ABSTRACT

In this paper, we present the experimental performance evaluations of a newly developed photoelectrochemical (PEC) reactor for the production of hydrogen under no-light and concentrated solar radiation conditions. With a newly developed experimental setup, the solar light is concentrated about ten times, and the spectrum is divided using cold mirrors for better sunlight utilization. The photoelectrochemical reactor is examined at different applied potentials and the hydrogen production quantities are measured. Copper oxide, which is used as a light-sensitive material, is electrochemically coated on the cathode metal plate to increase the rate of hydrogen evolution under illumination. The present experiments are conducted to investigate the variation of reactor performance with intensified light conditions and the obtained results are compared with the dark conditions. The results of this study reveal that the hydrogen evolution rate was 41.34 mg/h for concentrated light measurement and 34.73 mg/h for no-light measurements at 2.5 V applied potential. The corresponding photocurrent generated under concentrated light at 2.5 V is found to be 0.63 mA/cm^2. Under the concentrated sunlight, the hydrogen production rates increase considerably which is led by the positive effect of the photocurrent contribution.

Introduction

As a renewable and abundant supply, solar energy is a potential sustainable solution to the growing energy demands of the world with an addition of a storage technique. Solar energy is intermittent source with day/night cycles. Therefore, solar energy is desired to be stored in a different form of energy in order to deliver an uninterrupted supply. As a chemical fuel, hydrogen is an encouraging storage medium.

Photoelectrochemical hydrogen production is a major category under renewable energy-based hydrogen production options. Increasing the solar utilization has the capability to enhance the overall efficiency of solar-to-useful commodities conversion. Photoelectrochemical cells transform solar energy to hydrogen using light enthused electrochemical processes. In a photoelectrochemical cell, solar light is absorbed by one or both of the photo electrodes in which one of them is at least a semiconductor. Photoelectrochemical cells may generate either chemical or electrical energy depending on the

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desire of the usage. Light utilization ability can be decided by band gap of the material for the photo electrode. There are natural losses related with any solar energy transformation methods including the reasons caused by the materials [1,2].

Photochemical water reduction requires the flat-band potential of the semiconductor exceeding the oxidation potential of water of 1.23 V at pH = 0 or 0.82 V at pH = 7. A single band gap device requires, at a minimum, a semiconductor with a 1.6–1.7 eV band gap in order to produce the open circuit potential required to split water. When other voltage loss issues are also taken into account, a band gap of above 2 eV is usually essential [3]. The utilization of two semiconductor materials stays as an attractive choice for capturing a large share of the solar spectrum, with the two band gaps tuned to absorb corresponding sections of the solar spectrum [3]. Alternatively, using spectrum splitters, the multi-product generation can be increased leading higher overall efficiencies. In this respect, a brief review of the related studies in the literature is presented in the following paragraphs.

Lopes et al. [4] studied a PEC cell for testing different photoelectrodes configurations, appropriate for continuous operation and for easily collecting the produced gases. Photocurrent–voltage characteristics were obtained for all samples characterized under three different conditions namely no membrane separating the anode and the cathode evolution; using a Teflon® diaphragm and using a Nafion®212 membrane. The proposed Teflon diaphragm was successfully implemented in the new PEC cell, with around 47% photocurrent density enhancement when transparent WO_3 photoelectrode was used. Minggu et al. [5] expressed in their study that the main requirement for the photocell or photoreactor is to allow maximum light to reach the photoelectrode. They studied an overview of the photoelectrode configurations and the possible photocell and photoreactor design for hydrogen production by PEC water splitting. The ideal design of the photocell and photoreactor is such that the photoelectrode has a maximum exposure to light.

Ismail et al. [6] indicated in their review paper that hydrogen generation from water splitting by UV and visible light-driven photocatalysis has been a potential development in the area. Acar et al. [7,8] conducted energy, exergy and cost analyses studies for a continuous type hybrid photoelectrochemical hydrogen production system which generates Cl_2 and NaOH as useful commodities in addition to hydrogen. The efficiency of the integrated system was calculated as 4% with annual production of 2.8 kg of hydrogen per square meter of heliostat. Acar et al. [8] also analyzed a continuous type hybrid system thermodynamically for hydrogen generation which photoelectrochemically splits water and performs chloralkali electrolysis.

There is a dilemma between two key necessities of a photoelectrode in a tandem cell arrangement, namely, high transparency and high photocurrent density. To attain a solar-to-hydrogen (STH) efficiency beyond 10%, the photoelectrode of the front cell in tandem devices is desired to be absorptive to efficiently use photons from the sunlight while also being transparent enough to feed the rear cell for unaided operation. The efficiencies of the PEC cells are previously reported in the literature. Shi et al. [9] demonstrated a 7.1% solar-to-hydrogen conversion efficiency without any external potential mentioning one of the highest efficiency to date for a PEC/solar cell tandem device. Döscher et al. [10] proposed a standardized PEC characterization to provide crucial insights and guidance for developing tandem devices. The IPCE analysis shows a practical maximum of about 10% solar-to-hydrogen efficiency for the classical upright epitaxial GaInP/GaAs tandem PEC design. Li and Wu [11] prepared a review for the current status of the PEC water splitting semiconductors. TiO_2 is photochemically stable under harsh condition. However, owing to its large band gap, it can only absorb the ultraviolet (UV) light, which accounts for <5% of solar radiation. This leads to a very low theoretical maximum STH efficiency ranging between 1.3% and 2.2%. Therefore, different doping mechanisms are under investigation. Fe_2O_3 has an ideal band gap (1.9–2.2 eV) thus can achieve a theoretical maximum solar-to-hydrogen efficiency of 12.9%.

Photoelectrodes are commonly produced by depositing a thin sheet of semiconductor materials on top of the substrate via a conducting top surface. The substrate can be visible conducting glass, such as fluorine-doped tin oxide (FTO) [12–15] or a metal piece [16]. New techniques have been recognized to make photoelectrodes with improved qualities in which the morphology and other features of the semiconductor materials could be precisely supervised and regulated, involving anodization [17], radio-frequency (RF) magnetron sputtering [18], hydrothermal growth method [12], electrophoretic deposition [16], atomic layer deposition [15].

Spectral splitting applications are partially studied in the literature for various purposes. Mojiri et al. [19] introduced a method which filters sunlight for high temperature hybrid solar receivers and is employed in linear solar concentrators. The researchers combined a semiconductor doped glass with propylene glycol to work instantaneously as the heat transfer fluid and a band pass filter to set the optimal wavelength band, 700–1100 nm, in order to fulfill the silicon solar cells requirements of operation. An et al. [20] experimentally investigated solar spectrum splitting through the utilization of a Cu_9S_5 nano fluid as an optical filter for solar PV/T collectors. In this method, it was possible to reach efficiencies about 34.2% which is practically the double of the ones analyzed in non-filtered experiments. In a recent study, promising photoelectrochemical electrodes of CoO nanowires and cocatalyst (Ag) modified CoO nanowires were prepared and studied in photoelectrochemical water splitting exhibiting an efficient photoelectrochemical activity [21]. Graphene quantum dots onto metal oxide electron transport layer finds great deal of attention in solar light driven photoelectrochemical (PEC) hydrogen fuel generation. A study proposed colloidal graphene quantum dots (GQDs) as effective sensitizers of TiO_2 hollow nanowires for enhancing the light harvesting efficiency and the catalytic activity for water oxidation of this material. This provides a promising demonstration of concept of hybrid architecture for water photo-oxidation, without the need of sacrificial agents [22].

Previously, we have reported the electrochemical performance analysis and various different experimental results of the current PEC reactor [23–25]. In this study, a photoelectrochemical hydrogen production reactor is built having a large membrane surface area. The designed and developed photoelectrochemical hydrogen production reactor is one of

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