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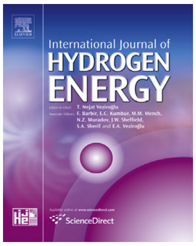

Autonomous hydrogen production system

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ABSTRACT

A system for hydrogen production via water electrolysis using solar energy has been designed and is presented in this paper. Investigations were related to the experimental measurements and modeling of the 60 W electrolyzer and 100 W PV module separately and, subsequently, as coupled system. The goal of this paper was to increase system efficiency while simplifying the system's design. Electrolyzer features related to operating temperature, voltage and electric current were investigated in detail. In the mathematical model of the electrolyzer, important parameters were determined based on UI characteristics, which included the electrolyte ohmic resistance, the electrode overvoltage, and the electrode active surface. Experimentation allowed the authors to improve the mathematical model of the electrolyzer. It clear explains phenomena of variable temperature in real conditions due to the new steady state and higher temperature profile developing as process continues. This statement presents the main contribution of this work. It is supported with experiments and explained in detail through the paper. With efficiency of 77.06% the experimental systems of the electrolyzer and PV module are designed to be roughly compatible with each other. The emphasis is to describe the important parameters in both systems. All mathematical models were programmed in Simulink/MATLAB software.

Introduction

An energy system based on fossil fuels is known to be unsustainable. Due to the increase in global temperature, rational energy use and carbon dioxide (CO_2) storage are methods that are trying to make the current system sustainable for a longer period of time. However, the transition to a sustainable energy system is inevitable [1]. The Hydrogen Economy is a synonym for a sustainable energy system in which pure hydrogen replaces fossil fuels (i.e., hydrocarbons) [2,3]. Hydrogen is a very clean source of energy; however, to yield a successful and sustainable energy system, hydrogen must be produced using renewable energy sources (RES), such as solar energy [4,5]. Compared to the intermittence of solar energy, hydrogen is a great energy carrier and storage medium [6]. Therefore, hydrogen could successfully replace fossil fuels [7]. Currently, the Hydrogen Economy has been legislated into the well-known goal of the European Union (EU) concerning of the long-term energy policy of 20-20-20 by the year of 2020. Thus, hydrogen production technologies, distribution, storage and utilization will have an important role in producing energy in the near future.

There are many different hydrogen production technologies including fuel processing, non-reforming hydrogen production and hydrogen from water. Currently the most used technology is the reforming of fossil fuels with efficiency up to

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85% but with highest air emissions. In order to switch to the low emission technologies, i.e. CO_2 free processes, significant development in other hydrogen production technologies is in permanent increase [7]. Producing hydrogen via water electrolysis using solar energy is currently the only commercial technique with zero CO_2 emissions. From an economical perspective, the ratio of the price of reforming and electrolysis is 1:3. However by including carbon tax which reaches values up to 50 $/kg, hydrogen production via water electrolysis becomes far more competitive [8]. Approximately 50 million tons of hydrogen usable as an energy source is equivalent to 170 million gallons of oil. For example, if all primary energy consumed per year in the Republic of Croatia (i.e., 200 PJ) were produced instead with hydrogen, which has a lower heating value of $H_L = 120$ kJ kg^{-1}, 1.667 billion tons of hydrogen would be required. Hence, the production of hydrogen from fossil fuels is valid only during a transitional period from the infrastructures of today to the sustainable energy system based on the RES of tomorrow, which will likely involve solar energy. Hydrogen production via water electrolysis using solar energy is essential from the aspect of energy supply security and environmental protection. There are certain integral technologies that are common to systems of this type: photovoltaic (PV) solar cells, an electrolyzer, hydrogen storage, a hydrogen fuel cell and water (i.e., the main operating fluid). Recent data today shows that out of the 246 hydrogen power plants worldwide, 72 (29.3%) produce hydrogen via water electrolysis. Out of these 72, 20 hydrogen power plants (27.8%) produce hydrogen via water electrolysis using PV cells (i.e., solar energy). Therefore, this work focuses on the design of an alkaline electrolyzer that uses potassium hydroxide (KOH) solution as an electrolyte. As long as electrolyzer can be designed as electrolyzer stack, its hydrogen production capacity is increasing [9]. With up to 66% power-to-hydrogen-efficiency capital costs for alkaline electrolysis are projected at 1400 $/kW, even still high but with a trend to significant decreasing to 2020 [10–13]. This paper discusses the experimental results according to the formulated objectives and hypothesis, offering solutions for further development and improvement. From a broader perspective, this research develops a method for designing two components (i.e., an electrolyzer and PV modules) into a system for hydrogen production that uses water electrolysis powered by solar energy (i.e., a PVH_2 system). This type of system is simpler, more reliable, cheaper and more effective compared to the similar existing systems for hydrogen production without CO_2 emissions. According to many experts, hydrogen is the fuel of the future, but its limited application in energy and transport has already begun in technologically developed countries worldwide. The autonomous PVH_2 system presented here has been designed, constructed and installed in the Laboratory of Power Engineering at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia [14].

Experimental set up

A laboratory-designed PVH_2 system was designed. Each component is laboratory made with basic material of Plexiglas®. This system consists of a 60 W single-pair monopolar alkaline electrolyzer consisted of two inner plates of 150 × 150 × 5 mm, two external plates of 150 × 150 × 12 mm and flat rubber seals of 150 × 150 × 1 mm, a 100 W PV module as electrolyzer power supply, a subsystem for electrolyte circulation (including separators, storage, centrifugal pumps, 50 W PV module used as pumps power supply, filter and electrolyte) and a subsystem for data collection (including data acquisition and computer). Horizontal design of separators is applied as cylindrical shape with built-in compartments. Storage vessels are designed as two-part storage with upper part of Φ134 × 128 mm and bottom part of Φ185 × 179 mm. Electrolyzer, gas separators and storage vessels are all made from Plexiglas®. Software used for data collection is LabView Signal Express. The electrodes of the electrolyzer are constructed of a Ni metal foam material that has an area of 0.0025 m^2 and a resulting surface area of 3.5 m^2 due to its porosity. Membrane used in electrolyzer is made of Zirfon® of Φ120 mm with thickness of 0.4 mm. The schematic diagram of the system is shown in Fig. 1. This system produces hydrogen autonomously with zero CO_2 emissions.

In Fig. 1 components of the PVH_2 system are highlighted as numbers. Their description is given in *Legend* as well as description of 22 measuring points. Used terms of H_2 site and O_2 site are related to the hydrogen and oxygen production respectively.

Legend

Description of PVH2 system components: **1**. Electrolyzer; 2. PV module as power supply for electrolyzer; 3. PV module as power supply for pumps; 4. Laboratory DC power supply; 5 Main switch; 6. DC/PV switch; 7a. H_2 centrifugal pump; 7b. O_2 centrifugal pum; 8a. H_2 site – filter; 8b. O_2 site – filter; 9a. H_2 site – flowmeter; 9b. O_2 site - flowmeter; 10a. H_2 separator; 10b. O_2 separator; 11a. H_2 storage; 11b. O_2 storage; 12a. H_2 site - electrolyte storage; 12b. O_2 site - electrolyte storage; 13a. H_2 site – shunt; 13b. O_2 site – shunt; 14. Shunt for electrolyzer; 15. Shunt for PV module; 16. Data aquisition; 17. Laptop

Description of measuring points: a) Solar irradiance; b) Ambient temperature of PV module; c) Temperature of PV cell; d) Operating voltage of PV module; e) Operating electric current of PV module; f) Operating electric current of electrolyter; g) Operating voltage of electrolyzer; h) Ambient temperature of electrolyzer; i) Pressure in O_2 storage; j) Temperature in O_2 storage; k) H_2 site – output electrolyte temperature; l) O_2 site – output electrolyte temperature; m) O_2 site - operating electric current of pump motor; n) O_2 site – operating voltage of pump motor; o) O_2 site – flow of electrolyte; p) O_2 site – input electrolyte temperature; q) H_2 site – input electrolyte temperature; r) H_2 site – flow of electrolyte; s) H_2 site – operating voltage of pump motor; t) H_2 site – operating electric current of pump motor; u) Temperature in H_2 storage; v) Pressure in H_2 storage

To produce an effective coupled PVH_2 system, a DC/DC converter is usually used to adjust the operating power of the PV module to power the electrolyzer. However, this was done without electronics to reduce costs by up to 700 USD per kW and simplify the system. The electricity supply system is composed of two PV modules located on the roof of the Laboratory; one is used for the electrolyzer, and the other for the two centrifugal pumps. A separate power supply is connected