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Experimental investigation of a hydrogen production system using photovoltaic electrolysis process

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Abstract. The purpose of this article is the experimental performance investigation of an electrolysis system connected to photovoltaic module for hydrogen production. Experimental setup includes a 90 W photovoltaic module and an electrolysis system. The various climatic and operating parameters of the experimental setup including solar radiation intensity, ambient temperature, wind speed, photovoltaic module temperature, electrolysis temperature, produced electrical power, consumed electrical power, hydrogen production rate and etc. are measured. The energy efficiency of combined system is introduced by writing energy balance for the general control volume of the system. Finally, parametric studies are carried out on the obtained experimental data. The daily energy efficiency of the system is less than 2.5 %. Since, the maximum value of electrical power of photovoltaic module occurs at noon; therefore, the maximum value of hydrogen production is obtained in this time and it is 0.78 ml/s. In addition, the experimental results of the present study show that nevertheless the energy efficiency of combined system is low but the usage of photovoltaic electrolysis process for hydrogen production has high potential capacities. Also, the energy efficiency of combined system and hydrogen production rate can be increased by equipping the electrolysis system of the present study to PEM, the usage of suitable electrolyte solution and cooling the photovoltaic module in order to reduce its electrical power loss.

Key words. Hydrogen production, electrolysis system, energy efficiency, photovoltaic module
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1. Introduction

Nowadays, hydrogen is used as a clean fuel widely. The matter of producing hydrogen with the consumption of fossil fuels emerged the problem of environmental pollution. So, examining the hydrogen production using renewable energies resources

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is so important. Solar energy is one of the most important renewable energies. Producing hydrogen using solar energy as primary non-fossil energy source and electrolysis system is available by several methods. Two main methods to use solar energy to produce hydrogen include:

1–Production of electrical power by thermal power plant and connecting it to the water electrolysis.

2–Production of electrical power by photovoltaic modules and connecting it to the water electrolysis. Producing hydrogen by photovoltaic electrolysis process has high potential in the future, because most of advanced technologies are related to it. In addition, photovoltaic process has several advantages. One of the advantages is that direct electrical current is produced by photovoltaic module and can be used directly in the electrolysis device. Hydrogen production system using photovoltaic electrolysis is one of methods which expected to reduce environmental pollution caused by fossil fuels and ultimately reduce the global warming. The cost of hydrogen production is high in this system; therefore, it should be worked in high efficiency. The performance investigation of photovoltaic electrolysis systems is so important to increase its efficiency. Several theoretical and empirical studies have been done in the field of performance evaluation of photovoltaic electrolysis system.

Ulleberg and Mørner in 1997 simulated a system of hybrid solar hydrogen production [1]. The components of hybrid system include photovoltaic module, electrolysis, fuel cell, acid battery, solar collector, hydrogen and water storage tanks, convertor and inventor of DC/AC. The purpose of simulating the hybrid system is to determine the dimensions of system to supply energy in a building in Trondheim in Norway. From their calculations the dimensions of the hybrid system to supply the energy in building were obtained very large, because the solar radiation intensity is low in Norway. Ulleberg and Pryor, in 2002 simulated a hybrid system to produce hydrogen [2]. The system includes electrolysis, hydrogen fuel cell, diesel motor and wind turbine. They used TRNSYS software to simulate the system. The results of simulation showed that the efficiency of hybrid system of hydrogen fuel cell-diesel-wind is more than hybrid system of diesel-wind. Conibeer, and Richards in 2007 compared the hydrogen production by photovoltaic electrolysis process and photo-electrolyte process [3]. The results of their analysis showed that the efficiency of photovoltaic electrolysis process is two times more than photo-electrolyte process. The advantages of photo-electrolyte process are simplicity of design and low cost. Clarke et al. in 2009 investigated the performance of a photovoltaic production system [4]. Their system included 31 photovoltaic modules connected parallel and a PEM electrolysis. Set of photovoltaic modules produce 2.4 kW of electrical power. Their results in RMIT University in Australia lead to produce $91\,\mathrm{m}^3$ of hydrogen within 60 days and the empirical efficiency was close to the efficiency of system theory. Djafour et al. in 2011 investigated the performance of photovoltaic electrolysis system in the laboratory scale [5]. Their results showed that the low efficiency of photovoltaic modules and the mismatch of electrolysis system led to decreasing the total efficiency in the system. García-Valverde, et al. in 2012 simulated a PEM electrolysis system for engineering applications [6]. Their simulation model was able to predict operating temperature, density of input current and dynamic behavior of hydrogen production precisely. Ghribi et al. in 2013 examined the hydrogen production by a PEM electrolysis connected to photovoltaic module [7]. Their system includes a 60 W photovoltaic module, a 50 W PEM electrolysis system, DC/DC electrical convertor and maximum power point tracer. They estimated the hydrogen production annually 20–29 m^3. Su et al. in 2014 investigated how to arrange photovoltaic modules in the photovoltaic electrolysis system appropriately [8]. They investigated three different configurations to connect six photovoltaic modules in summer, autumn and winter in Beijing at China. Their results showed that the best arrangement of photovoltaic modules include output hydrogen production annually 74.7 kWh/m^2.

Ganeshan et al. in 2015 investigated an electrical current regulator on the production level of hydrogen in a photovoltaic electrolysis system [9]. Their hybrid system includes a set of 60 W photovoltaic modules and 30 W electrolysis. Their results showed that using an electrical current regulator stabilizes input electrical current to the electrolysis and lead to produce hydrogen with constant rate even in variable solar radiation intensity. Constant hydrogen rate is important for auxiliary system which uses the produced hydrogen to produce power.

Various electrolytes are used in the electrolysis system. Electrolytes are responsible to facilitate the performance of electrolysis process. In the previous studies [1–9], electrolytes type has been investigated less. Acid electrolytes causing corrosion the electrodes in the system when increasing the speed of reaction and this is undesirable. The purpose of this study is to examine the performance of photovoltaic electrolysis system with the laboratory scale to produce hydrogen in Zahedan city. In this study, alkaline electrolyte of potassium hydroxide was used to solve the mentioned problem. The mixture ratio of the mentioned electrolyte with water is obtained within several primary experiments about 30 percent.

2. Energy analysis

Figure 1 shows the electrolysis system connected to photovoltaic module in Department of Mechanical Engineering, University of Sistan and Baluchestan.

The experiment setup includes a 90 W photovoltaic module made in Electronic Sazan Company and a 60 W electrolysis of laboratory scale made in United Nuclear Company. The measured experimental data include solar radiation intensity, wind speed, ambient temperature, photovoltaic module temperature, electrolysis temperature, produced electrical power, consumed electrical power and hydrogen production rate.

The measurement tools are digital luxmeter (TES-1339R), infrared thermometer (FLUDE-62), digital anemometer (LM-8000), three digital thermometers (Buit-In-Thermometer-40..+110C), the flow meter of gas of APASCO company (GMP) and two digital multi-meters (Victor-DT9205). Figure 2 shows the total control volume of hybrid system and its different energy components.

The energy balance equation for control volume of Fig. 2 is as follows:

$$\sum \dot{E}n_{\mathrm{in}} - \sum \dot{E}n_{\mathrm{out}} = \left(\frac{\mathrm{d}En}{\mathrm{d}t}\right)_{\mathrm{cv}} . \tag{1}$$

Fig. 1. Electrolysis system connected to photovoltaic module in Department of Mechanical Engineering, University of Sistan and Baluchestan

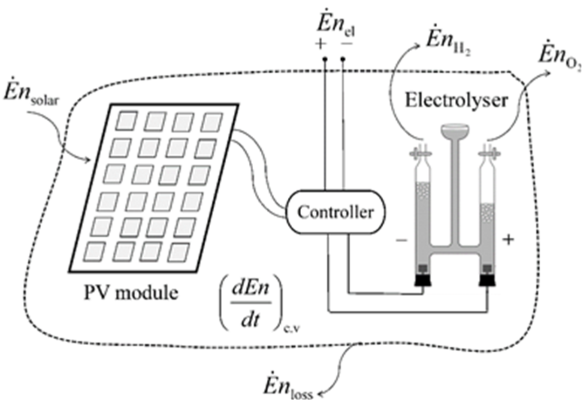

Fig. 2. Electrolysis system connected to photovoltaic module in Department of Mechanical Engineering, University of Sistan and Baluchestan

Here $\sum \dot{E}n_{\mathrm{in}}$, $\sum \dot{E}n_{\mathrm{out}}$ and $\left(\frac{\mathrm{d}En}{\mathrm{d}t}\right)_{\mathrm{cv}}$ are input energy rate to control volume, output energy rate from control volume and the rate of energy changes in the control volume, respectively. Placing different components of energy rate in equation (1) yields

$$\dot{E}n_{\mathrm{solar}} - \dot{E}n_{\mathrm{H_2}} - \dot{E}n_{\mathrm{O_2}} - \dot{E}n_{\mathrm{el}} - \dot{E}n_{\mathrm{loss}} = \left(\frac{\mathrm{d}En}{\mathrm{d}t}\right)_{\mathrm{cv}}, \tag{2}$$

or

$$GA_{\mathrm{PV}} - \dot{m}_{\mathrm{H_2}}h_{\mathrm{H_2}} - \dot{m}_{\mathrm{O_2}}h_{\mathrm{O_2}} - (P_{\mathrm{mp}} - P_{\mathrm{L}}) - \dot{E}n_{\mathrm{loss}} = \left(\frac{\mathrm{d}En}{\mathrm{d}t}\right)_{\mathrm{cv}}, \tag{3}$$

where G, A_{PV}, $\dot{m}_{\mathrm{H_2}}$, $\dot{m}_{\mathrm{O_2}}$, $h_{\mathrm{H_2}}$, $h_{\mathrm{O_2}}$, P_{mp}, P_{L} and $\dot{E}n_{\mathrm{loss}}$ are solar radiation intensity, photovoltaic module area, mass flow rate of hydrogen, mass flow rate of oxygen, enthalpy of hydrogen flow, enthalpy of oxygen flow, produced electrical power of photovoltaic module, consumed electrical power of electrolysis and the rate of thermal loss from the control volume, respectively. The rate of thermal loss includes convection and radiation loss from the control volume. The energy efficiency of hybrid system is defined as ratio of desired output energy rate to input net energy rate to system

$$\eta_{\mathrm{en}} = \frac{\dot{E}n_{\mathrm{desired}}}{\dot{E}n_{\mathrm{in,net}}}\,. \tag{4}$$

The rate of desired output energy of photovoltaic electrolysis system includes the rate of output hydrogen flow and the difference of produced and consumed electrical power. In other hand, the rate of net input energy to system includes the solar energy entering to photovoltaic module. Replacing the related statement in equation (4), the energy efficiency of the hybrid system is obtained as follows:

$$\eta_{\mathrm{en}} = \frac{\dot{m}_{\mathrm{H_2}} h_{\mathrm{H_2}} + (P_{\mathrm{mp}} - P_{\mathrm{L}})}{GA_{\mathrm{PV}}} = 1 - \frac{\dot{m}_{\mathrm{O_2}} h_{\mathrm{O_2}} + \left(\frac{\mathrm{d}En}{\mathrm{d}t}\right)_{\mathrm{cv}}}{GA_{\mathrm{PV}}}\,. \tag{5}$$

3. Results

The experiments was done on the sunny days in spring in 2015 in the roof of Department of Mechanical Engineering, University of Sistan and Baluchestan, Zahedan, Iran from 8 am to 4 pm. Measurement of the data was done in one hour interval time. Figure 3 shows the data of solar radiation intensity and wind speed in term of the experiment time.

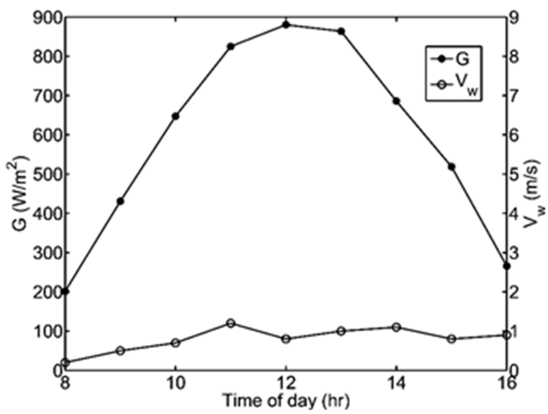

Fig. 3. The data of solar radiation intensity and wind speed in term of the experiment time

According to Fig. 3, the highest solar radiation intensity occurred in the noon and wind speed in the experiment day was relative quite.

In Fig. 4 photovoltaic module temperature, electrolysis temperature and the ambient temperature is shown based on experiment time.

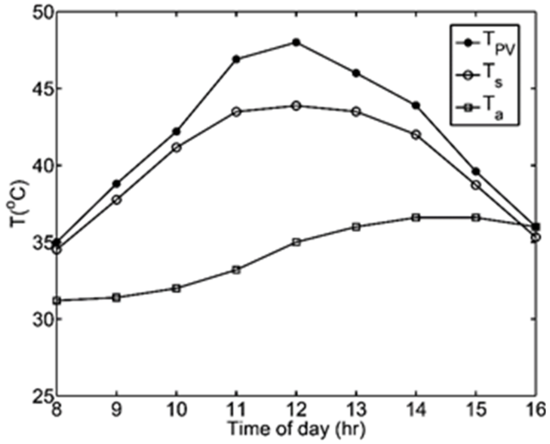

Fig. 4. Temperature of photovoltaic module, electrolysis temperature and ambient temperature versus experiment time

In Fig. 4, parameters such as $T_{\rm PV}$, $T_{\rm s}$ and $T_{\rm a}$ indicate photovoltaic module temperature, electrolysis temperature and ambient temperature, respectively. According to the figure, the temperature of electrolysis is constant from 11 to 13. The used electrolysis system has 60 W of consumption electrical power. In the mentioned time, photovoltaic module produce 70 W of electrical power and electrolysis device cannot consume all produced electrical power of photovoltaic module. So, the electrolysis temperature is increased until about 43 °C due to the limited capacity of electrolysis system in electrical power consumption.

Figure 5 shows the electrical power of photovoltaic module and the consumed electrical power of electrolysis based on the experiment time.

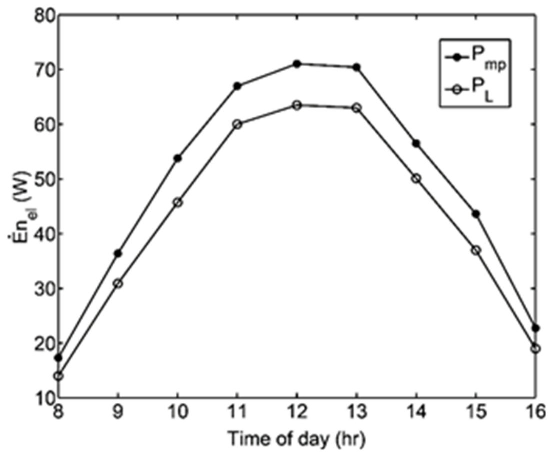

Fig. 5. Electrical power of photovoltaic module and the consumed electrical power of electrolysis based on the experiment time

According to Fig. 5, the highest produced electrical power of photovoltaic module is occurred at noon. In this time, there is higher solar radiation intensity and the electrical current of photovoltaic module is maximized. Therefore the electrical power of photovoltaic module increases. On the other hand, increasing solar radiation intensity increases the temperature of photovoltaic module and the consequence of it the output voltage photovoltaic module is decreased. In this time, photovoltaic module cannot provide their maximum nominal electrical power (90 W). In the noon, the consumed electrical power of electrolysis is constant about 60 W. The capacity of electrolysis device in this experiment is limited and work in maximized power. Totally, in most of time electrolysis device consume more than 80 percent of produced electrical power by photovoltaic module.

Figure 6 shows hydrogen flow rate based on experiment time.

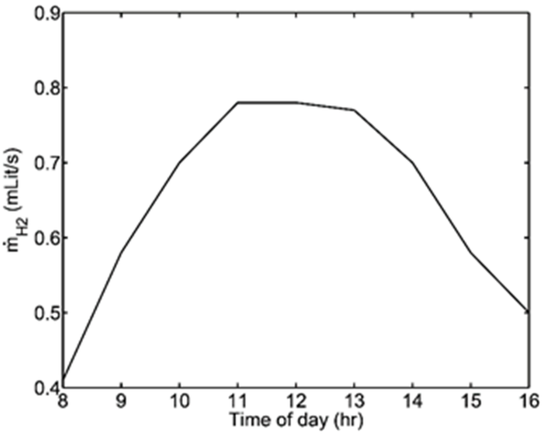

Fig. 6. Changes of hydrogen production rate according to experiment time

Based on Fig. 6, highest value of hydrogen production is related to noon which electrolysis device is working at high capacity. Given the limited capacity of electrolysis device, there is upper limit for hydrogen production which is 0.78 ml/s.

In Fig. 7, the changes of energy efficiency of hybrid system based on experiment time is shown.

According to the figure, the lowest energy efficiency of the system is occurred at noon. There is high hydrogen production rate and electrical power of photovoltaic module at this time, but this increase lead to increasing the intensity of solar radiation and reduce the energy efficiency of in the noon. This matter is due to increasing photovoltaic module temperature and electrolysis device temperature and ultimately the loss of energy of control volume is increased. Generally, the efficiency of hybrid system is less than 2.5 percent.

4. Conclusion

This study investigated the performance of hydrogen production system using photovoltaic electrolysis process. Climate and operating parameters of hybrid system

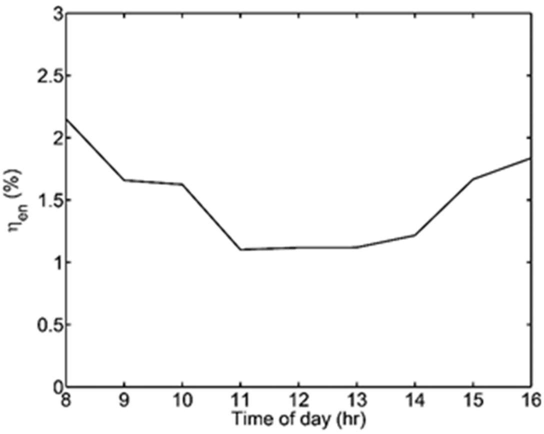

Fig. 7. Changes of energy efficiency of hybrid system based on experiment time

were measured and the obtained data were analysed. The results are provided as following based on the experimental study:

In the experiment, the electrolysis device consumes more than 80 % of electrical power produced by photovoltaic module.

There is an upper limit for hydrogen production and its maximum value is 0.78 ml/s.

When the energy efficiency of hybrid system is low (lower 2.5 %), using solar energy and lack of environmental pollution are main advantages of hybrid system. Using photovoltaic electrolysis process to produce hydrogen has high potential capacities. To increase the efficiency of energy in hybrid system, it is recommended to use PEM electrolysis device and desired electrolyte solution and cooling photovoltaic module by PV/T collector.

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