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PERFORMANCE OF HYDROGEN PRODUCTION PROCESS USING SOLAR ENERGY

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ABSTRACT

The present experimental work is devoted to explore the efficiency of alkaline water electrolysis in producing hydrogen when it is operated by solar energy. The overall system efficiency is determined by measuring the solar irradiance as the source of the input energy, and the amount of hydrogen produced as the source of the output energy. Hence, the losses through the Photo-Voltaic (PV) cell, connecting wires, and the water electrolyzer, are all considered in the present study. Moreover, the effects of the gab width distance and the separators' types, on the overall system efficiency are also presented. It is found that, the higher the electrolyzer efficiency, the higher is the overall system efficiency at almost conditions. The significant reduction in system efficiency may be due to losses of the energy conversion through the PV cell and the electrical losses in the connecting wires. Though, the electrolyzer efficiency reaches 90% and the maximum overall system efficiency of 1.7% is barely achieved.

KEY WORDS

Hydrogen production; System efficiency; Electrolyzer efficiency; and Solar energy.

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INTRODUCTION

The challenges of climate change and the depletion of fossil fuel trigger the pressing need to use renewable energy sources, instead of the traditional sources of energy. The recent energy systems need to be sustainable, efficient, convenient, clean and safe. One of the future energy carriers that could meet these requirements is the hydrogen, with the advantages of being transportable, storable and converting energy with practically no release of environmental pollutant. It is the fuel that is expected to replace conventional liquid and gaseous fuels in stationary and transport applications [**1-2**]. Hydrogen contains more energy as natural gas, though with clean combustion. It produces only water vapour, and hence, it is pollution free. However, the resources of this gas, as a pure gas, are not generally found in nature and it must be regenerated. Hydrogen is always found in the form of compounds and external energy is consumed for its production.

Hydrogen can be produced from water via water electrolyzer using renewable energy as the external energy source [**3-4**]. Hence, the complete system in this case, has no release of environmental pollutants. Among renewables, several studies have been published on the production of hydrogen using solar energy **[5]**. This can be achieved by using PV cell, coupled with the water electrolyzer. Hydrogen production, using this technique, has the advantage of the direct supply of DC electrical power produced from the PV cell to the water electrolyzer. Various experimental and numerical studies were performed on photovoltaic-electrolyzer systems [**6-9**].

The performance of the PV hydrogen system, with hydrogen as energy storage and fuel cell as a regenerative system, is explored by Lehman et al [**10**]. They discussed also, the safety and the maintenance of the operating system. The average electrolysis efficiency of 76.7% and hydrogen production efficiency of 6.2% are achieved. The increase in photovoltaic module current, which is directly affected by the solar radiation intensity, increases the hydrogen production flow rate by El Shenawy and Ahmad [11].

In addition, Balabel et al. [**12]** investigated the electrolyzer efficiency at various operational parameters, by experimental and numerical studies. The experimental results of Mahrous et al. [**13**] showed that the performance of water electrolyzer unit is highly affected by input voltage and the gap between the electrodes. Also, the effect of the separator material, separation distance and solution concentration on energy efficiency of alkaline water electrolyzer, were investigated by Sakr et al. **[14]**. Higher system efficiency was gained at smaller gap distances between the pair of electrodes [**13-14**]. Furthermore, the use of potassium hydroxide (KOH) as an electrolyte leaded to better hydrogen production. High concentrations of the ionic liquid was found to produce hydrogen more efficiently. The numerical study of El-Askary et al. [15] showed that, the hydrogen production is maximized by decreasing the main flow velocity. They also reported that, the increase of the current density accompanied by the reduction in gap distance between the two electrodes could raise up the hydrogen production process.

The present work aims to experimentally explore the efficiency of the solar-driven water electrolyzer system in producing hydrogen. A photovoltaic PV cell is used to directly supply the electric power to the electrodes. The efficiencies of the PV cell, water electrolyzer, and overall system are all presented and discussed.

THE SOLAR-HYDROGEN SYSTEM

The solar-hydrogen system presented in the current work consists of water electrolyzer as hydrogen generator, which is driven directly by electric power from a Photo-Voltaic PV cell as shown in Fig. 1. The PV module is BYD255P6C-30 (60 cells), with rated power of 225 W under Standard Test Conditions (STC). The open circuit voltage is 38.07 V and the short circuit current is 8.89 A. The operating temperature range is 40-85° C. The electrolyzer model is composed of two electrodes known as anode (A) and cathode (C), which are made of stainless steel and located on left and right sides of the cavity, respectively. The electrodes have a surface area of 4 cm² (2 x 2), and they are immersed vertically in the electrolyte using an isolated (coated) spindles fitted on the upper surface of the electrolyzer chamber. The electrolyzer box is fabricated by acrylic with inner dimensions of (30 x 15 x 15) cm^3 and wall thickness of one cm. The gap distance between the electrodes is set to be δ. The cavity contains an electrolyte which is a dilute solution of Potassium Hydroxide (KOH) of 30% solution concentration. A measured electric current from solar energy passing through the two electrodes disassociates KOH into K^+ and OH^- ions. Hydrogen gas evolves at the cathode while oxygen gas forms at the anode according to the following electrochemical reactions:

At the cathode:

$$4H_2O + 4e^- \rightarrow 2H_2(gas) + 4OH^- \tag{1}$$

At the anode:

$$4OH^- \rightarrow O_2(gas) + 4e^- + 2H_2O \tag{2}$$

The electrodes are connected to the photovoltaic module directly by connecting wires. Hydrogen and oxygen gases are then collected separately by displacing the saturated water in a bubbler under atmospheric pressure.

Different instruments are used for calculating the efficiencies of the PV cell, water electrolyzer, and overall system as the following;

The PV cell efficiency η_{PV} is defined as;

$$\eta_{PV} = \frac{E_{solar}}{E_{PV}} = \frac{Solar\ irradiance \times Area\ of\ \ PV\ cell}{V_{PV} I} \tag{3}$$

In order to obtain η_{PV}, a thermopile pyranometer (model EPPLEY PSP) is used to measure the solar irradiance, with a range of 0-2000 W/m^2 and ± 10% uncertainty. The PV module voltage V_{PV} is measured using DC Voltammeter CHY CY-33L with a range of 0-20 V and ± 0.3 – 0.4 % accuracy. The current is measured using DC Ammeter CD771 with a range of 0-20 A and ± 2 % accuracy.

The efficiency of the electrolyzer η_e is defined in [14] as;

$$\eta_e = \frac{E_{H_2}}{E_{el}} \tag{4}$$

where, E_{H_2} is the energy content in the amount of hydrogen produced as defined by Sakr et al. [14], and E_{el} is the electrical energy supplied to the electrolyzer, to produce the same amount of hydrogen.

In order to obtain η_e, the input voltage to the water electrolyzer V_e is measured using a similar DC Voltameter CHY CY-33L as used for the above PV cell. The current flowing in the wire is the same, and hence, the input current to the electrolyzer is the same as the output current from the PV cell. Further, the volume of hydrogen produced is measured every thirty minutes by a Sensitive Balance (volume), self-manufactured with a volume of 2 L and an accuracy of ±1%. The corresponding electrolyzer efficiency is calculated based on the measured electrical energy supplied during that period.

The overall system efficiency η_s is defined as:

$$\eta_s = \frac{E_{H_2}}{E_{solar}} \tag{5}$$

Now, the energy content in the produced hydrogen and the input solar energy to the system are available. Hence, the system overall efficiency can be calculated from the above relation.

RESULTS AND DISCUSSION

In the present work, the electrolyzer box is divided into two chambers by either an acrylic separator of 1.0 mm thickness or a polypropylene separator of 0.4 mm thickness. The gap distance between the two opposite electrodes (anode and cathode) is set to be either 5 mm or 10 mm. The measurements are performed on solution concentration of 30%.

Figure 2 illustrates the variation of the PV cell voltage and the solar irradiance with time, during the day 5 June 2017. It is shown that the increase in solar irradiance causes an increase in the output volt from the PV cell. However, the same amount of solar radiation may result in different output voltage values, depending on the other operating parameters, including the cell current and the operation temperature.

The efficiency of PV cell during operation through the day time is presented in Fig. 3, when using two different separator types and separation distances. It is observed that, η_{PV} varies between 7 to 8 % at most of the operation time. The change of the gap distance (δ) and separator type between the electrodes has no obvious effect on the trend of the PV cell efficiency. The maximum PV cell efficiency is achieved at the evening with peak of 12.9%.

Figure 4 introduces the efficiencies of operation for both the electrolyzer η_e and the overall system η_s. The efficiencies are presented for the two separator types (acrylic and polymeric) for gap distance (δ) of 5 mm. The electrolyzer efficiency during the operation period is higher when using polymeric membrane, as compared to acrylic separator. This may be caused by higher resistance of acrylic separator to ions transfer, as compared to the polymeric membrane. The same observation is attained also for the whole system, as the overall system efficiency is higher for the polymeric membrane electrolysis cell. Hence, the system of higher electrolyzer efficiency has the best performance. However, it is noticed that, the system efficiency is very low, due to the low efficiency of the PV cell, see Fig. 3. Although the electrolyzer efficiency reaches 86% for polymeric separator, the maximum obtained η_s is 1.16%. Similar trends are obtained for separation distance of 10 mm as shown in Fig. 5, however with higher efficiency values. The electrolyzer efficiency reaches 90% for polymeric separator with maximum system efficiency of 1.67%. The difference in η_s between the two separator types tends to be less, except at early morning hours.

The accumulated volume of hydrogen production during the day time measurements is presented in Figs. 6 and 7 for gap distances of 5 mm and 10 mm, respectively. It is shown that, the productivity using the poly membrane is higher than that obtained for acrylic separator. Furthermore, the rate of hydrogen production is found to be low at the later hours of the day time.

CONCLUSION

The current paper introduces an experimental investigation on solar hydrogen system to explore the efficiency of each of PV cell, water electrolyzer, and overall system. The solar irradiance, PV cell voltage and current, input voltage to the electrolyzer, and amount of hydrogen produced are all measured simultaneously during the present study. It is found that, the PV cell efficiency has a maximum value of 12.9%, though with 7 to 8% at most of the operation time. The significant reduction in system efficiency is due to losses of the energy conversion through the PV cell and the electrical losses in the connecting wires. Though, the electrolyzer efficiency reaches 90%, the maximum overall system efficiency of 1.67% is barely achieved. However, the higher the electrolyzer efficiency, the higher is the overall system efficiency.

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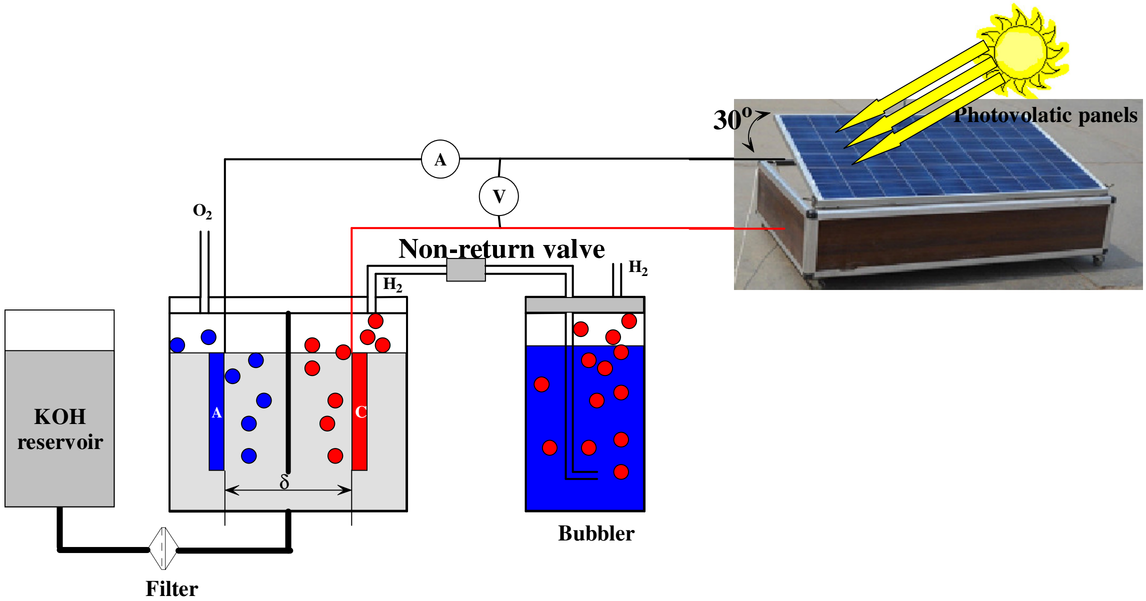

Fig. 1 Experimental arrangement of the solar hydrogen system.

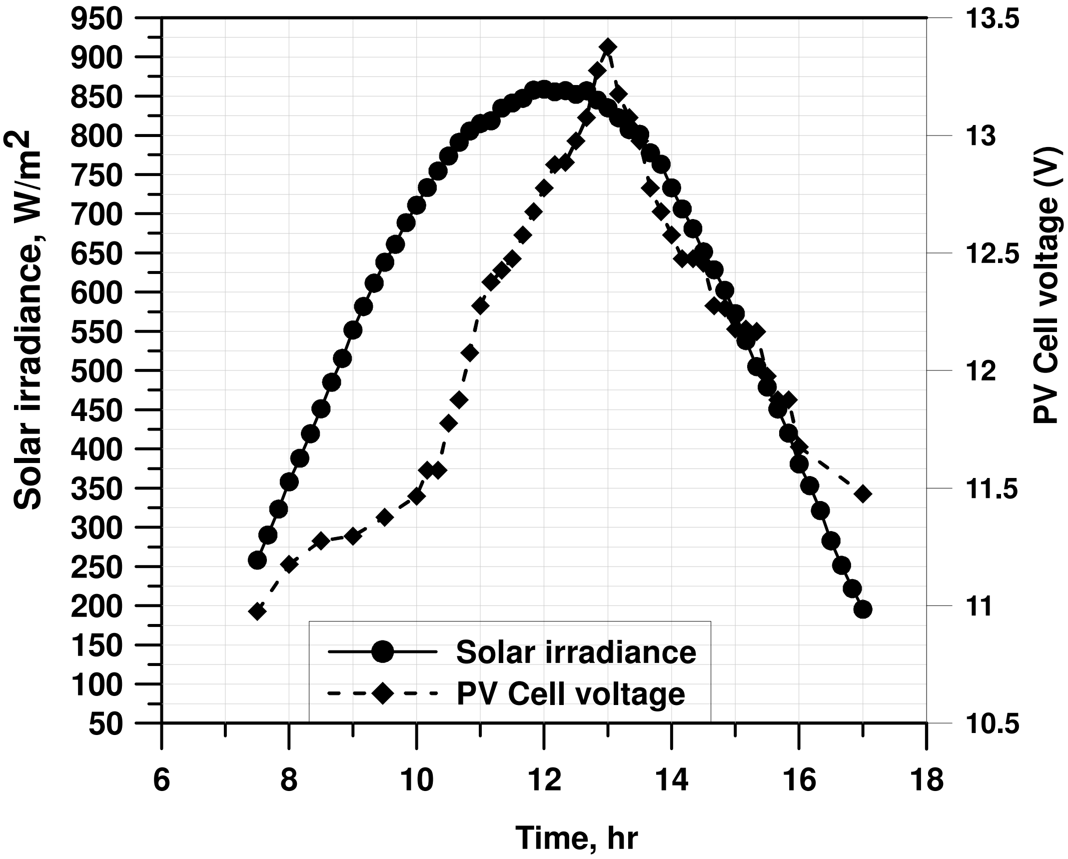

Fig. 2 Variation of solar irradiance and PV cell voltage through the day time.

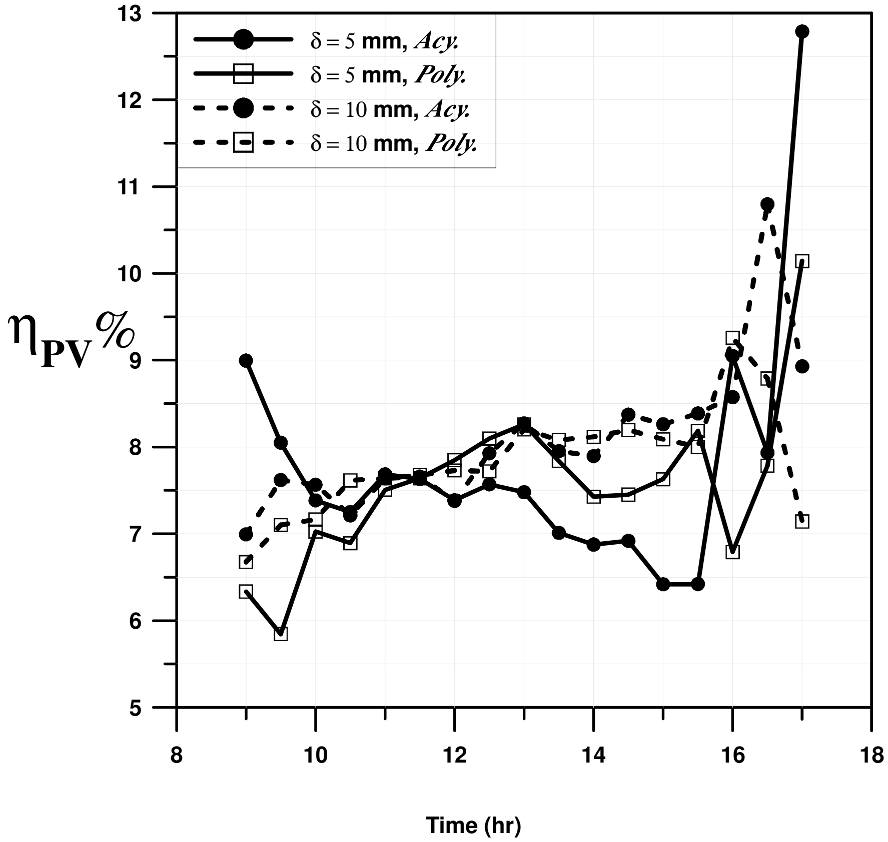

Fig. 3 PV cell efficiency at different water electrolyzer production units.

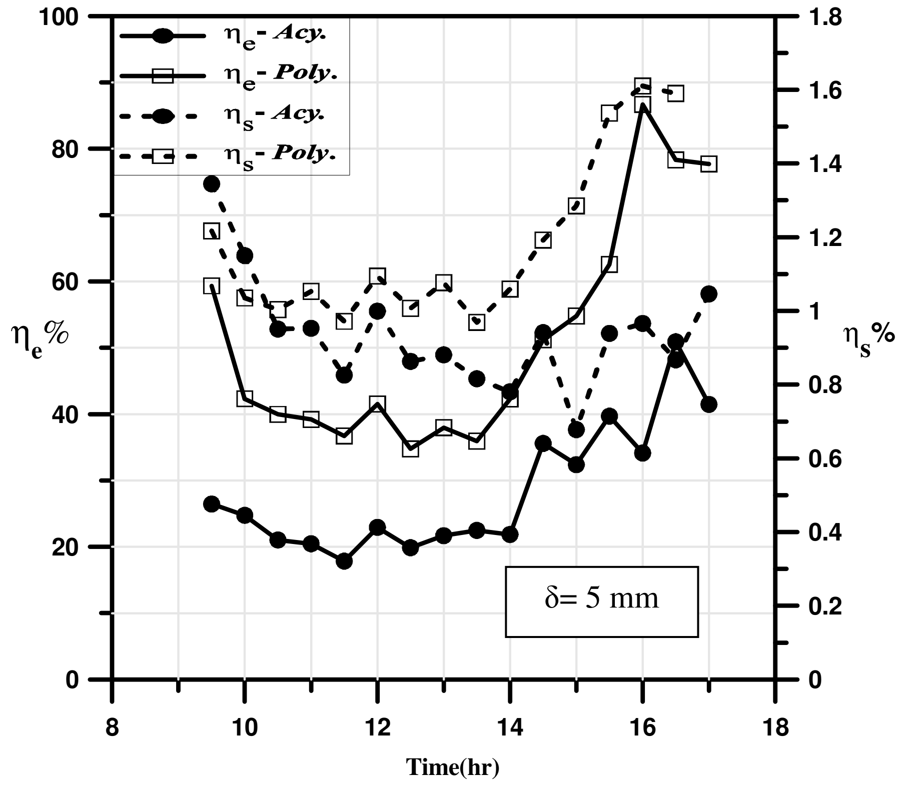

Fig. 4 Electrolyzer and overall system efficiencies at 5 mm gap distance between the two electrodes.

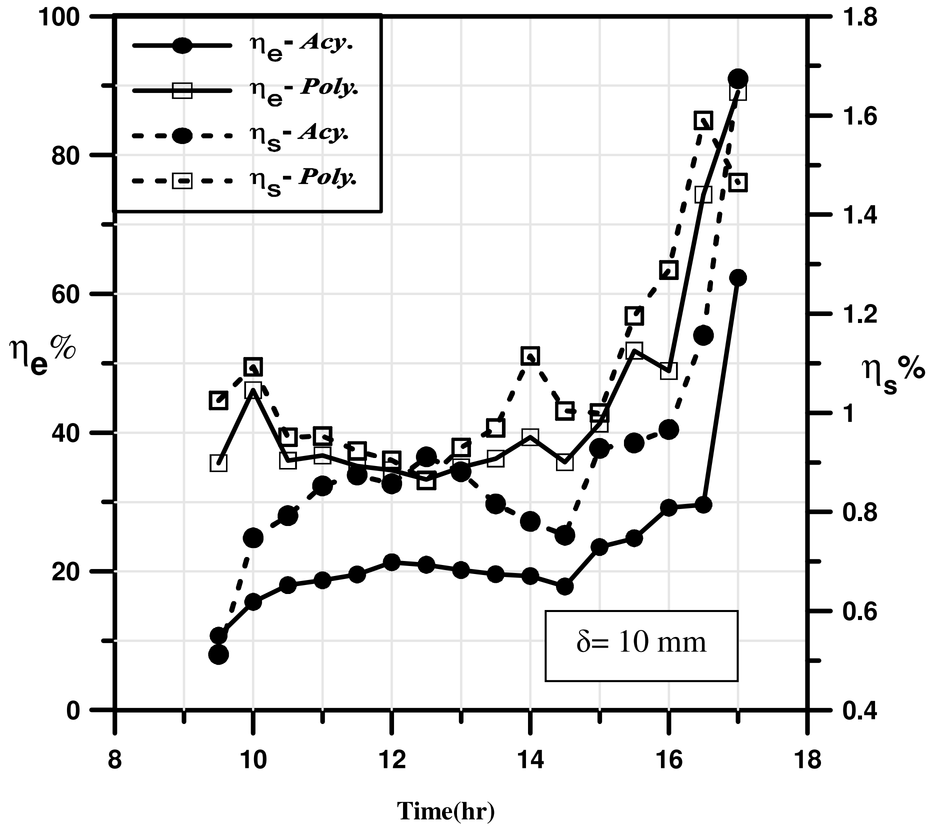

Fig. 5 Electrolyzer and overall system efficiencies at 10 mm gap distance between the two electrodes.

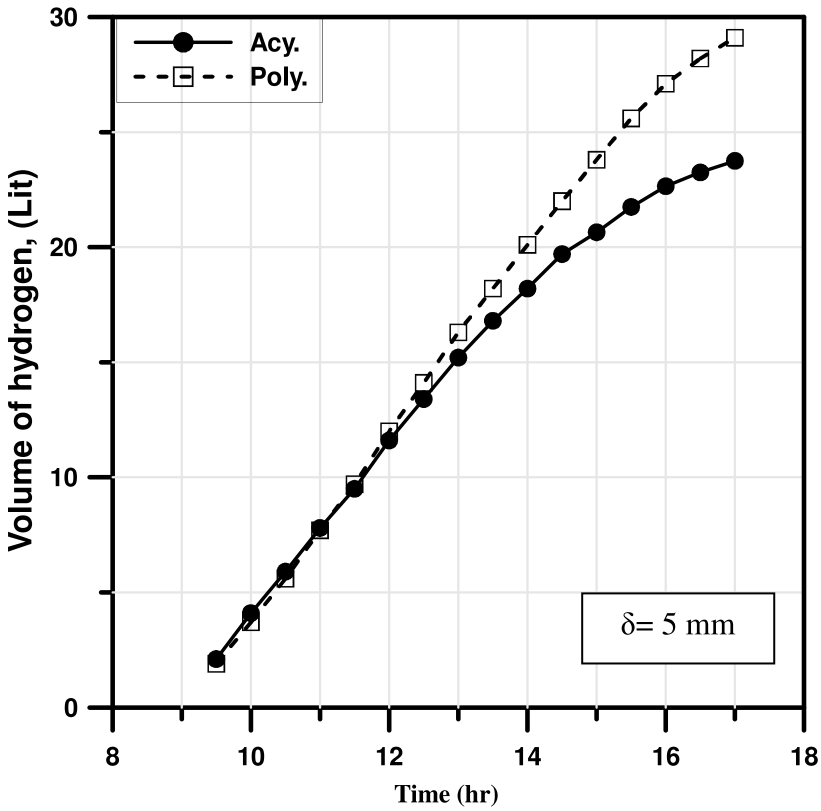

Fig. 6 Accumulated volume of hydrogen produced through the day time, at 5 mm gap distance between the two electrodes.

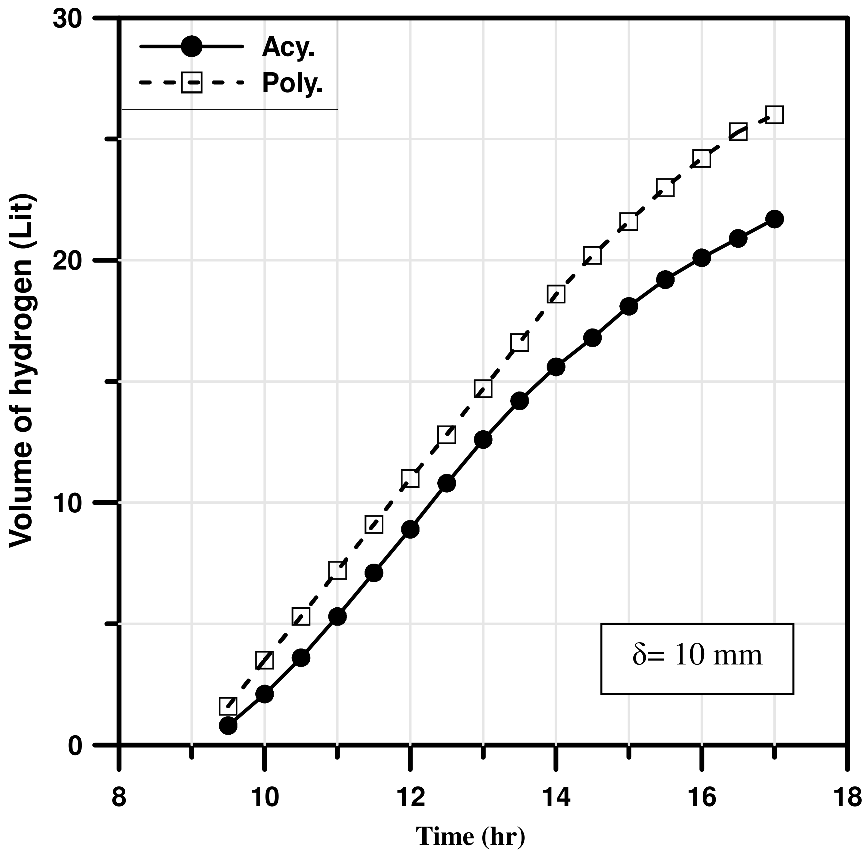

Fig. 7 Accumulated volume of hydrogen produced through the day time, at 10 mm gap distance between the two electrodes.