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Development of Water Electrolysis System for Hydrogen Production as a Renewable Source of Energy

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Abstract

The objective of this study is to develop and evaluate a simplified unit of water electrolysis for hydrogen production. Three type of water, (tap water add 10%wt KOH, sea water, sea water add 10%wt KOH) were used, and three distances between electrode (1, 2 and 3 mm) were used at surface area of the electrodes of 250 cm^2. Measurements were taken for energy requirement, produced energy, produced hydrogen, system efficiency and costs. The obtained results indicate that the produced energy for hydrogen production increases with increasing operating time, reaching the highest value of the energy requirement of hydrogen production (126 W h) was found with the sea water for 1 mm distance between electrodes. The highest value of the produced energy of water (254 W h) was found with the sea water add 10%wt KOH for 1 mm distance between electrodes. While, the lowest value of the produced energy of water (204 W h) was found with the sea water for 3 mm distance between electrodes. The highest value of the produced hydrogen of water (64 W h^{-1}) was found with the tap water add 10%wt KOH for 1 mm distance between electrodes. While, the lowest value of the produced hydrogen of water (23 L h^{-1}) was found with the sea water for 3 mm distance between electrodes. The total costs of hydrogen production unit decreases with an increase in the surface area of the electrodes. The total costs of hydrogen production were 0.55, 0.65 and 0.73 L.E L^{-1} for tap water add 10%wt KOH, sea water and sea water add 10%wt KOH, respectively.

Keywords: Hydrogen, Electrolysis, Renewable energy, Operating time, Potassium hydroxide.

1. Introduction

Hydrogen is an environmental-friendly energy carrier that is separated from water through electrolysis. Therefore, it has become necessary to improve hydrogen productivity at the lowest costs. Increasing anthropogenic activity has led to a significant surge in global energy consumption. The global energy consumption increases gradually due to the diverse increasing in human activities. Nowadays, most of the energy used generated from the fossil fuels which affect the environment due to the high carbon emissions which in turn cause climate changes. Renewable energy for hydrogen is considered one of the promising sources of environmentally friendly energy carrier and it has the potential to be the right choice to replace fossil fuels as the most usable energy fuel source **[2].**

Hydrogen could be obtained by electrolysis to spilt water or using biomass to emerge promising energy sources that can be produced in renewable mode **[6].**

It is obvious that the whole world must search, develop, and plan for alternative energy systems in both the short and long term. Hydrogen as a clean energy carrier, has become increasingly important **[3].**

Using renewable sources of energy in hydrogen production such as wind, solar photovoltaic cells can be economically feasible and contribute in solving environmental pollution problems **[11].** Currently, the demographic growth and industrial intervention has led to the increase of using the energy worldwide. Energy is necessary for the global economy and social modernization, and at present, approximately 65% of the worldwide energy requirement has been fulfilled by nonrenewable sources such as fossil fuels **[14].** Hydrogen is an important energy carrier with several roles in transportation, energy storage, and chemical processes **[1].**

Hydrogen is the lightest of the known elements and the most abundant gas in the universe, accounting for around 90% of the visible universe. Hydrogen has the maximum energy content of conventional fuels per unit of weight. Energy content of hydrogen is about 3x of that of gasoline **[18].**

Global energy consumption is expected to increase continuously in the next decades, driven by rising standards of living and growing population **[11].** Most of the hydrogen is consumed by fertilizer and petroleum industries. Because of its high heating value (142 kJ /g) and sustainable production, hydrogen has the potential as an alternative fuel source **[15].**

Hydrogen produced using renewable energy from offshore wind provides a versatile method of energy storage and power-to-gas concepts. However, few dedicated floating offshore electrolyser facilities currently exist and therefore conditions of the offshore environment on hydrogen production cost and efficiency remain uncertain **[4].**The role of natural gas as a provider of clean energy has been noticeably increased due to its low greenhouse gas emissions, versatility, high caloric value, and abundance **[8].**

The main aim of this study is to develop and evaluate a simplified unit of water electrolysis for hydrogen production. Test and evaluate the unit by studying some factors affecting in the performance of this unit such as three water type and three distances between electrodes.

2. Materials and Methods:

Experiment of this work was conducted at the Agricultural and Bio-Systems Engineering Department, Collage of Agriculture. Moshtohor, Benha University, Egypt. During the period of September to December, 2024.

2.1. Materials

2.1.1. Unit description:

Figures (1 and 2) show the hydrogen production unit. Which has an external cover, and cells (stainless steels) separated by interval of Gasket rubber flex, the unit is gathered with nails and has 2 openings for water entry and exit. The ingress of water between the positive and negative cells is separated into two hydrogen atom and oxygen atom. Hydrogen gas comes out of the top slot of the lid high water tank. Acrylic cover dimension 300 × 300 mm was used to cover and link the whole unit. The unit is provided by 5 L polyethylene water cylinder (φ16 cm diameter and 32 cm height) and a hose of 1 cm diameter was connected to the water tank upper opening through a small tube. There are three openings in the tank, one for delivering water to the cell, the other for collecting hydrogen from the cell, and the third for clearing hydrogen gas and collecting it in a reflex tube in a container filled with water and exposed to the atmosphere.

The unit was providing by energy using power supply of electricity to operate the hydrogen gas production unit. It used to convert from AC to DC. The outlet power of power supply is 12 Volts and 10 Amps.

Kutcher flexible Gaskets rectangular in shape were used for its guardian compression ratio. They were used to isolate the positive cells from the negative cells and prevent water leakage of the gas output. Local manufactured gaskets are available in various areas of 200, 300, and 400 cm^2. The gasket has dimensions of 21× 21 cm.

Hoses that made from plastic were used to connect between the opening of hydrogen produced and water tank. Check value was fixed on it to control the flow. Bolts and nuts were used to bind the components of unit cell to assure the power transferring through it.

2.Water analysis:

Table (1) shows the chemical and physical analysis of sea water and tap water respectively.

2.2. Methods:

2.2.1. Principles of electrolysis:

Equations from 1 to 5 show the electrochemical flow of water electrolysis as follows **[17].**

Water Electrolysis

Net Reaction: $H2O = H2 + 1/2\ O2$ (1)

-Acidic Reaction

Anode: $H_2O \rightarrow 1/2O_2 + 2H^+ + 2e^-$ (2)

Cathode: $2H^+ + 2e^- \rightarrow H_{2\ (gas)}$ (3)

-Alkaline Electrolysis

$2OH^- \rightarrow 1/2O_2 + H_2O + 2e^-$ (4)

$2H_2O + 2e^- \rightarrow H_{2\ (gas)} + 2OH^-$ (5)

Electrochemical pathway for acidic and saline electrolysis is to understand the principles of electrolysis, Perhaps the most basic experiments is the use of two pencils sharpened at both ends with the top being connected to a battery and the bottoms inserted into alkaline water. Illustration the concept is showing many bubbles appearing at the negative pencil and half that many appearing at the positive the reactions are:

Positive: $2OH- \rightarrow 1/2O2 + H2O + 2e$ (6)

Negative: $2H2O + 2e \rightarrow H2 + 2OH-$ (7)

2.2.2. Treatments:

The treatments include: Three type of water (tap water add 10%wt KOH, sea water and sea water add 10%wt KOH), and three distance between electrode (1, 2 and 3 mm) with 250 cm^2 surface areas of the electrodes.

2.2.3. Measurements:

The power requirements were determined by clamp meter to measure the line current (I) and the potential difference value (V):

$$P = \frac{Current\ (I) \times Potential\ (V) \times cos\,\theta}{1000} \quad (8)$$

Where:
P is the required power, kW
I is the line current, Amperes.
V is the potential difference, Voltage.
Cos θ is the power factor, equal 0.8.
Hydrogen produced was collected in a scaled flask and recorded each 10 min.
The unit efficiency was determined as follows according to **[10]:**

$$\eta = \frac{NH_2 \times HHV}{E} \times 100 \quad (9)$$

Where:
η is the efficiency of unit, %.
NH_2 is the rate of hydrogen production, kg h^{-1}.
HHV is the hydrogen high heating value, 39.40 kWh / kg.
E is the electric energy inputs, kW.
The hydrogen volume is determined as follows according to **[10]**:

$$VH_2\ \text{ideal} = \frac{I \times VM \times t}{2 \times F} \times 100 \quad (10)$$

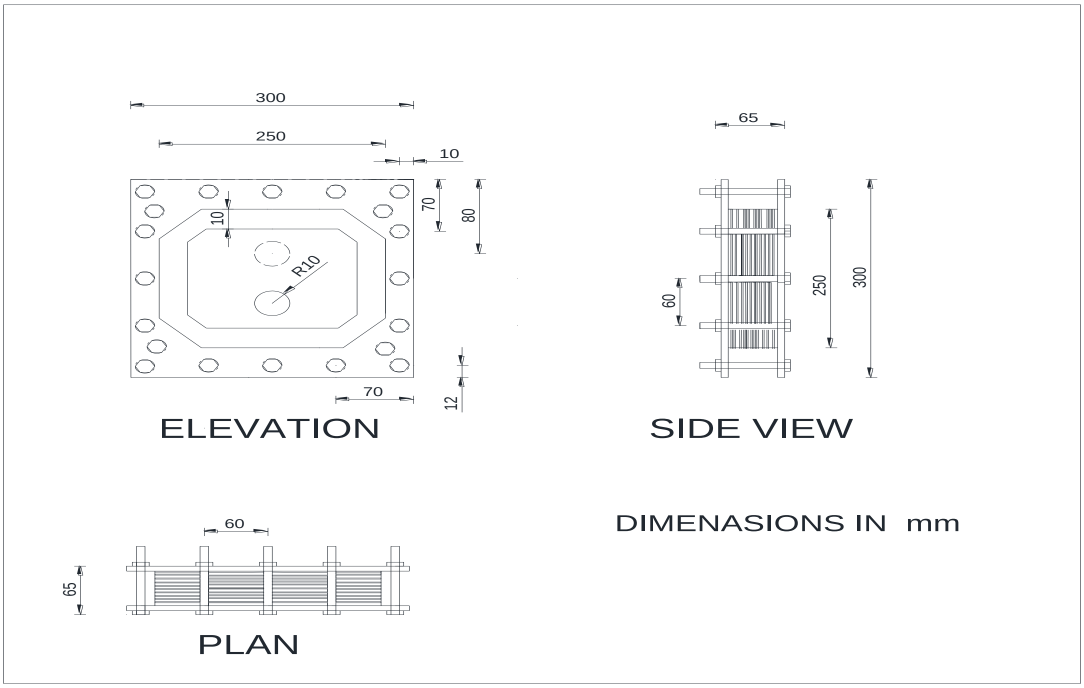

Fig (1): The experimental schematic diagram of electrical conduction for unit.

Fig (2): Photographic of the materials used for the hydrogen production unit.

Table (1): The chemical and physical analysis of tap and sea water.

Property	PH	TDS	Turbidity	Chlorides	Ca^{+2}	Fe	SO4	Mg^{+2}	Sodium
Sea Water	7.8	36000 ppm	0.3 NTU	23900 ppm	1040 ppm	0.2 ppm	62 ppm	N.D ppm	11150 CFU/100ml
Tap Water	6.5	190 ppm	0.4 NTU	114 ppm	N.D ppm	N.D ppm	9.8 ppm	Trace ppm	N.D CFU/100ml

Where:

I is the current (in Amps) passes through the cell during a period, t

VM is the molar volume of ideal gas under standard conditions, 298.15 K and 1 atm

F is Faraday's number, 96 485 C/mol

Hydrogen volume is determined from the following equation according to **[10].**

$$VH_2 \text{ real} = (VH_2 \text{ measured}) \frac{T \text{ standard}}{T \text{ measured}} \qquad (11)$$

Where:

VH_2 measured is the hydrogen volume

T standard is reference temperature, K

T measured temperature, K**.**

3.1.Total Costs

The total costs were determined using the following unit items:

- Depreciation costs (DC):

$$DC = \frac{\text{Pd+Sr}}{\text{Ld}} \qquad (1٢)$$

Where:

Dc is the depreciation cost, LE $year^{-1}$.

Pd is the purchase price, 10000 LE.

Sr is the salvage rate ($0.1P_d$) LE.

Ld is the unit life, 5 year.

- Interest costs (In):

$$In = \frac{\text{Pd+Si}}{2} * in \qquad (1٣)$$

Where:

In is the interest, LE $year^{-1}$.

in is the interest as compounded annually, decimal. (12%)

(Si) is: Shelter, taxes and insurance costs(LE $year^{-1}$):

The Si were assumed to be 3 % of the purchase price of the unit (Pd).

Then:

<u>Fixed cost (LE h^{-1})</u> = Dc + In + 0.03 Pd / hour of use per year (1٤)

- Repair and maintenance costs (R_m):

R_m = 100 % deprecation cost / hour of use per yea (1٥)

- Energy costs (E):

E = EC x EP (1٦)

Where:

E is the energy costs, LE h^{-1}.

EC is the electrical energy consumption, kWh.

EP is the energy price, 0.57 LE Kw / h.

-Labor costs (La):

La = Salary of one worker x No. of workers (1٧)

Where:

La is the Labor costs, LE h^{-1}.

Salary of one worker = 10 LE h^{-1}.

No. of workers = 1

Then:

Variable costs(LEh^{-1})=R_m+E+La (1٨)

Total costs (LE h^{-1}) = Fixed costs (LE h^{-1}) + Variable costs (LE h^{-1}) (1٩)

3. Results and Discussion

3.1.Energy requirements of hydrogen production:

Figure (3a, b and c) shows the accumulated energy requirement of hydrogen production at different type of water (tap water add 10%wt KOH, sea water and sea water add 10%wt KOH) and different at between electrodes (3, 2 and 1 mm) with 250 cm2 of surface area of the electrodes during the test. The energy requirement of hydrogen production increases with increasing operating time. It is also, refers that the energy requirement increases with adding potassium hydroxide concentration for different type of water during the experimental period. It could be seen that the energy requirement increased from 9 to 101, 4 to 86 and 8 to 107 W h, when the operating time increased from 10 to 110, 10 to 150 and 10 to 120 min for tap water add 10%wt KOH, sea water, sea water add10%wt KOH, respectively. The results refers that, the highest value of the energy requirement of hydrogen production (107 W h) was found with the sea water add 10%wt KOH after 120 min. While, the lowest value of the energy requirement of hydrogen production (86 W h) was found with the sea water after 150 min for 250 cm^2 of surface area of the electrodes.

For second level of distance between electrodes, the result refers that, the produced energy increased from 23 to 245, 13 to 215 and 19 to 214 W h, when the operating time increased from 10 to 100, 10 to 140 and 10 to 110 min for tap water add 10%wt KOH, sea water, sea water add 10%

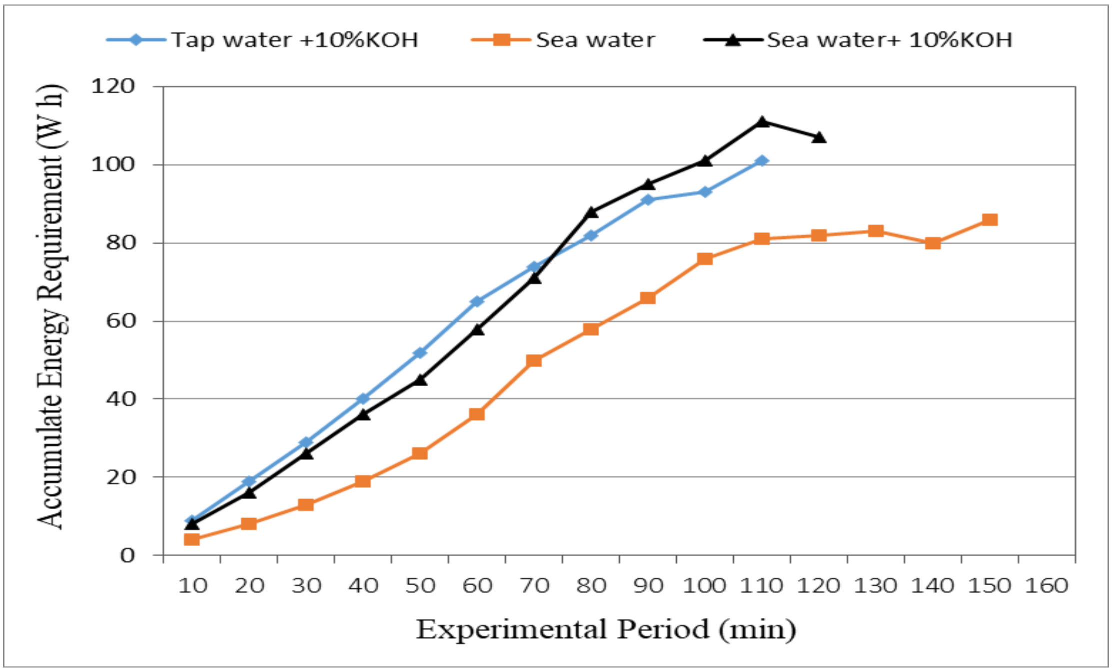

Fig. (3a): The energy requirement of hydrogen production at different type of water at third level distance between electrodes with 250 cm^2 of surface area of the electrodes.

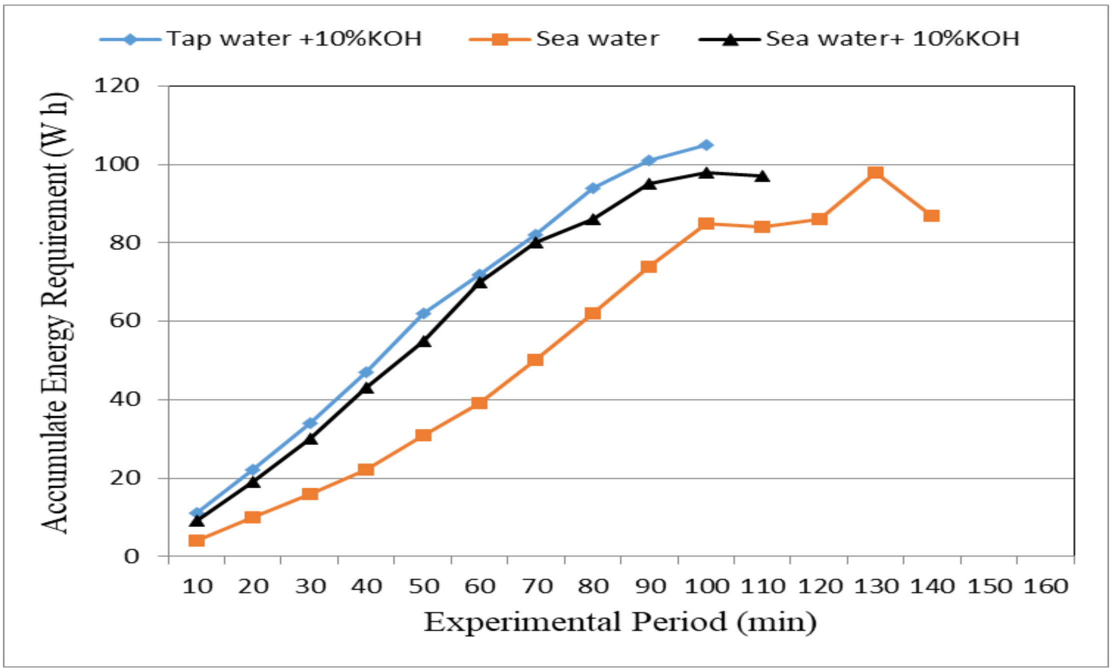

Fig. (3b): The energy requirement of hydrogen production at different type of water at second level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

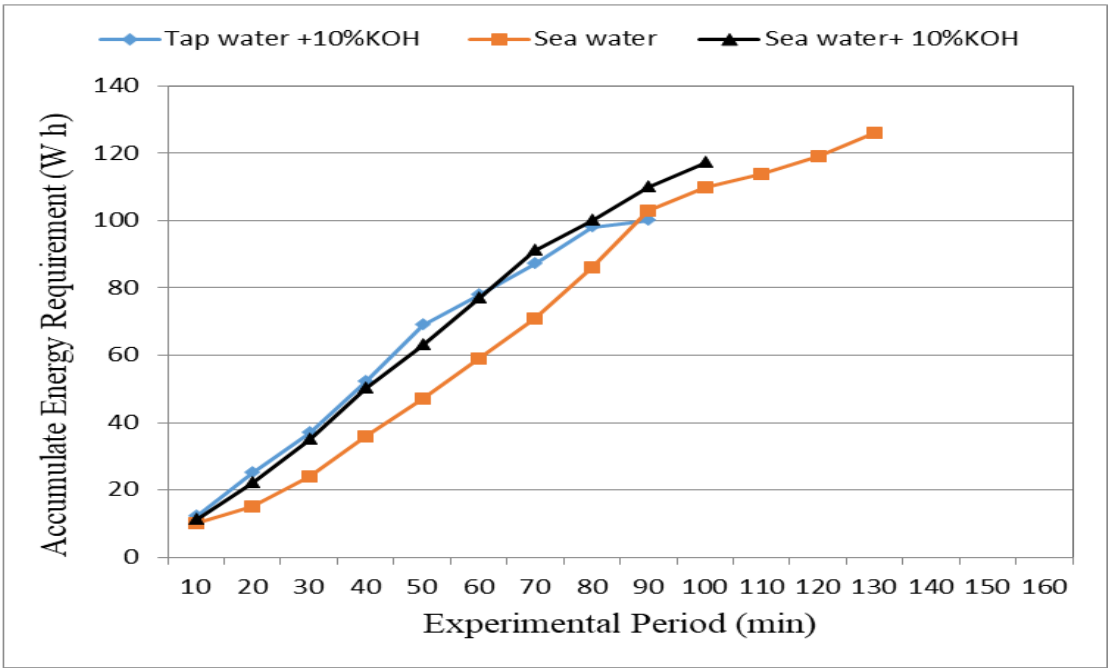

Fig. (3c): The energy requirement of hydrogen production at different type of water at 1distance between electrodes with 250 cm^2 of surface area of the electrodes.

KOH, respectively. The results refers that, the highest value of the energy requirement of hydrogen production (105 W h) was found with the tap water add 10%wt KOH after 100 min. While, the lowest value of the energy requirement of hydrogen production (87 W h) was found with the sea water after 140 min for 250 cm^2 of surface area of the electrodes.

For first level of distance between electrodes, the result refers that, the energy requirement increased from 12 to 100, 10 to 126 and 11 to 117 W h, when the operating time increased from 10 to 90, 10 to 130 and 10 to 100 min, respectively for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH. The results refer that, the highest value of the energy requirement of hydrogen production (126 W h) was found with the sea water after 130 min. While, the lowest value of the energy requirement of hydrogen production (100 W h) was found with the tap water add 10%wt KOH after 140 min for 250 cm^2 of surface area of the electrodes. These results are in agreement previous findings **[7].**

3.2. Accumulate produced energy of water:

Figure (4a, b and c) shows the accumulated produced energy of water at different type of water (tap water add 10%wt KOH, sea water and sea water add 10%wt KOH) and at different levels of distance between electrode (3, 2 and 1 mm) with 250 cm^2 of surface area of the electrodes. The produced energy increases with increasing operating time. It is also, refers that the produced energy increases with adding potassium hydroxide concentration for different type of water during the experimental period. It could be seen that the produced energy increased from 19 to 216, 11 to 204 and 16 to 220 W h, when the operating time increased from 10 to 110, 10 to 150 and 10 to 120 min, respectively for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH. The results refers that, the highest value of the produced energy (220 W h) was found with the sea water add 10%wt KOH after 120 min. While, the lowest value of the produced energy (204 W h) was found with the sea water after 150 min for 250 cm^2 of surface area of the electrodes. For second level of distance between electrodes, the result refers that, the produced energy increased from 23 to 245, 13 to 215 and 19 to 214 W h, when the operating time increased from 10 to 100, 10 to 140 and 10 to 110 min for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH, respectively. The results refers that, the highest value of the produced energy (245 W h) was found with the tap water add 10%wt KOH after 100 min. While, the lowest value of the produced energy (214 W h) was found with the sea water add 10%wt KOH after 110 min for 250 cm^2 of surface area of the electrodes. For first level of distance between electrodes, On the other hand, for first level of the produced energy increased from 26 to 219, 15 to 247 and 20 to 254 W h, when the operating time increased from 10 to 90, 10 to 130 and 10 to 100 min for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH, respectively. The results refer that, the highest value of the produced energy (254 W h) was found with the sea water add 10%wt KOH after 100 min. While, the lowest value of the produced energy (219 W h) was found with the tap water add 10%wt KOH after 90 min for 250 cm^2 of surface area of the

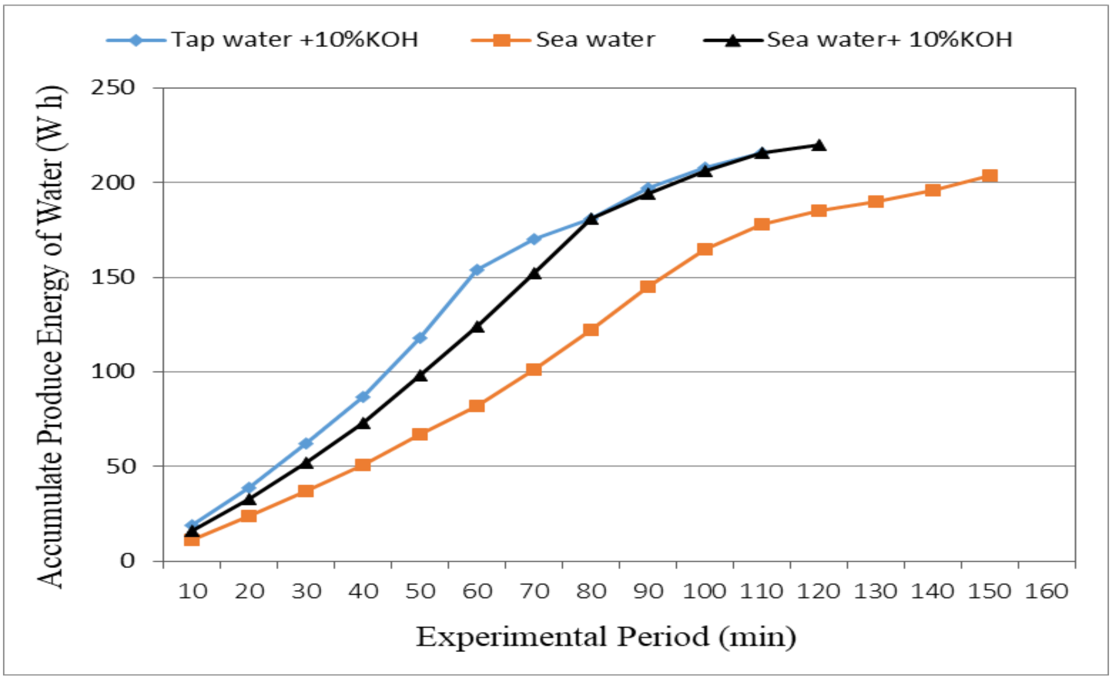

Fig. (4a): The produced energy of water at different type of water at third level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

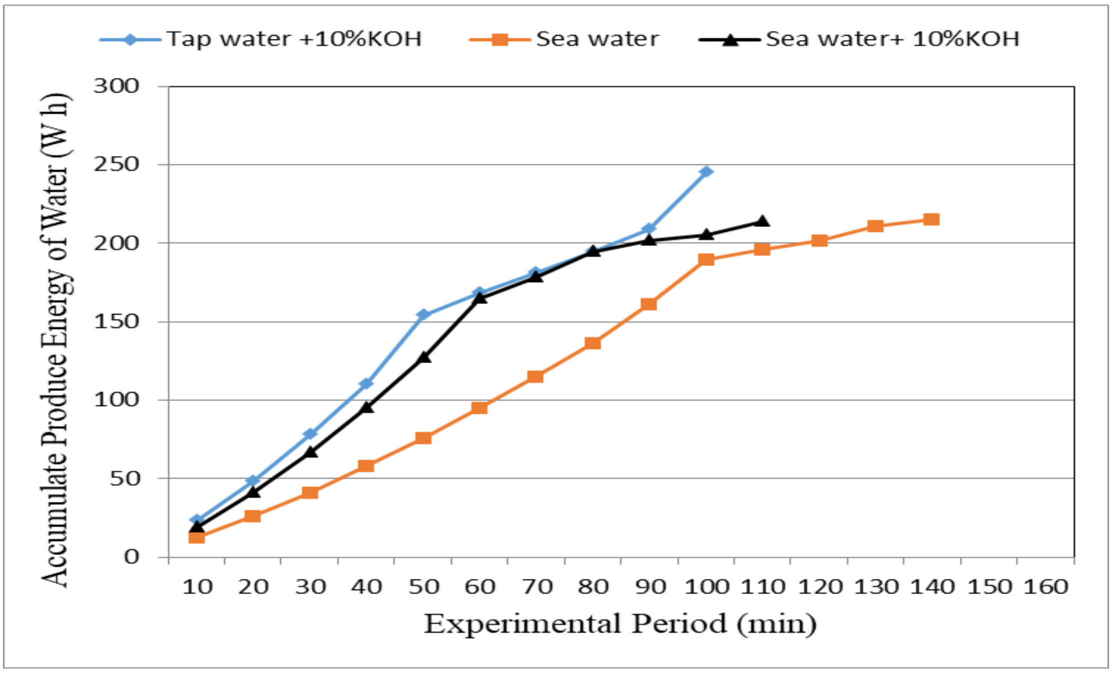

Fig. (4b): The produced energy of water at different type of water at second level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

the electrodes. These results are in agreement previous findings by **[12].**

3.3. Accumulate produced hydrogen of water:

Figure (5a, b and c) shows the accumulated produced hydrogen of water at different type of water (tap water add 10%wt KOH, sea water and sea water add 10%wt KOH) and at different levels of distance between electrodes (3, 2 and 1 mm) with 250 cm^2 of surface area of the electrodes during the test. The results refer that, the produced hydrogen increases with increasing operating time until it reached the peak and then decreased. It is also, refers that the produced hydrogen increases with adding potassium hydroxide for different type of water during the experimental period. It could be seen that the produced hydrogen increased from 32 to 43, 19 to 28 and 27 to 38 L h^{-1}, when the operating time increased from 10 to 60, 10 to 100 and 10 to 80

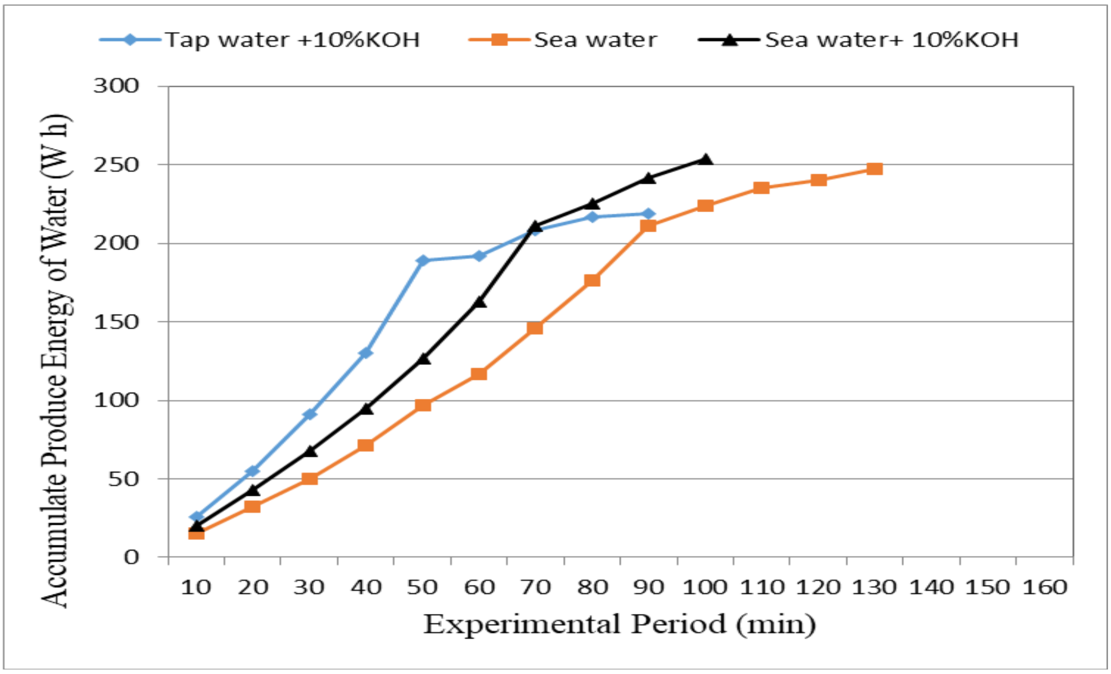

Fig.(4c): The produced energy of water at different type of water at first level a distance between electrodes with 250 cm^2 of surface area of the electrodes.

min, respectively for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH. The results refers that, the highest value of the produced hydrogen (43 L h^{-1}) was found with the tap water add 10%wt KOH after 60 min. While, the lowest value of the produced hydrogen (23 L h^{-1}) was found with the sea water after 150 min for 250 cm^2 of surface area of the electrodes. For second level of distance between electrodes, the result refers that, the produced hydrogen increased from 39 to 52, 22 to 32 and 32 to 47 L $^{-1}$, when the operating time increased from 10 to 50, 10 to 100 and 10 to 60 min for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH, respectively. The results refers that, the highest value of the produced

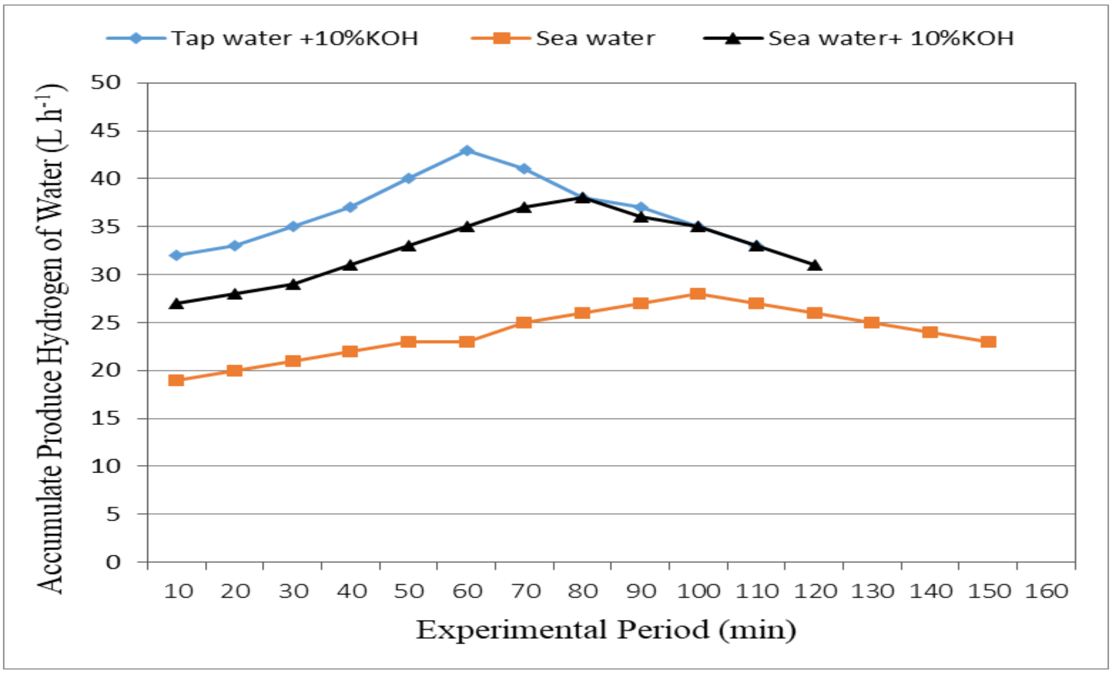

Fig. (5a): The produced hydrogen of water at different type of water at third level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

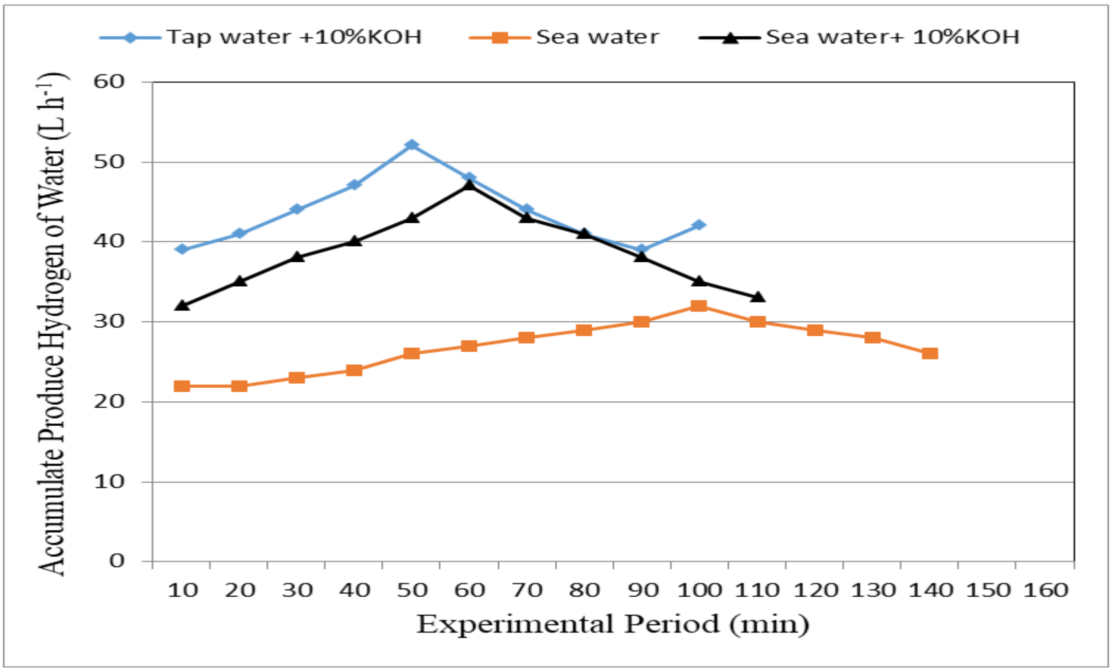

Fig. (5b): The produced hydrogen of water at different type of water at second level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

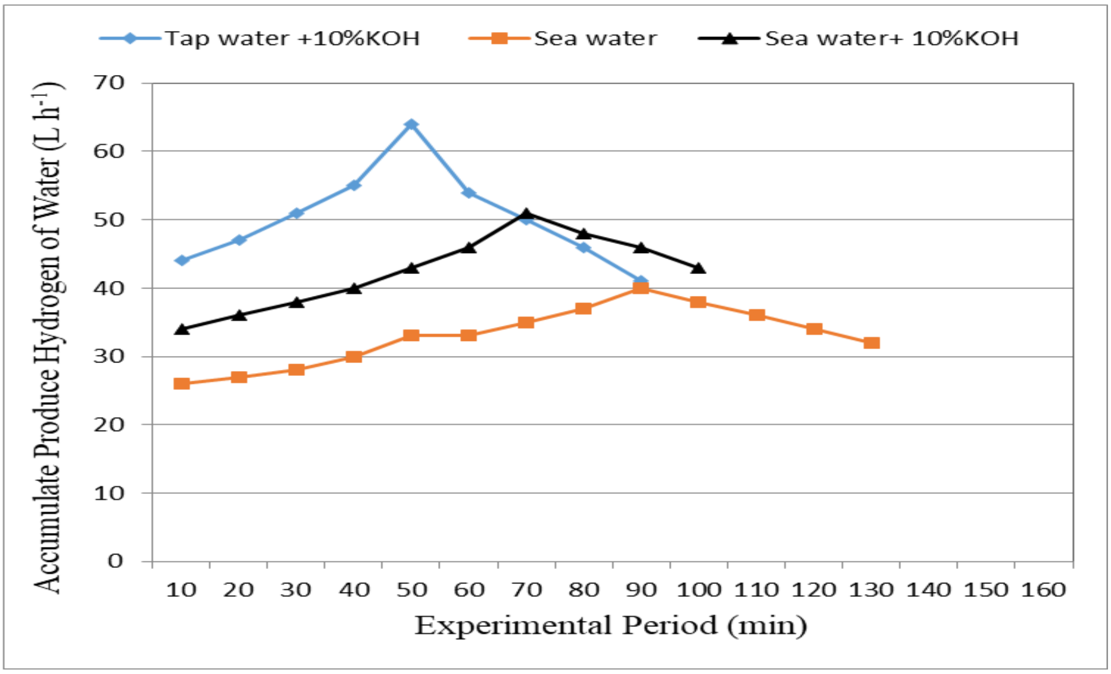

Fig. (5c): The produced hydrogen of water at different type of water at first level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

hydrogen (52 L h^{-1}) was found with the tap water add 10%wt KOH after 100 min. While, the lowest value of the produced hydrogen (26 L h^{-1}) was found with the sea water after 140 min for 250 cm^2 of surface area of the electrodes.

For first level of distance between electrodes, the result refers that, the produced hydrogen increased from 44 to 64, 26 to 40 and 34 to 51 L h^{-1}, when the operating time increased from 10 to 90, 10 to 130 and 10 to 100 min for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH, respectively. The results refer that, the highest value of the produced hydrogen (64 L h^{-1}) was found with the sea water after 130 min. While, the lowest value of the produced hydrogen (32 L h^{-1}) was found with the tap water add 10%wt KOH after 130 min for 250 cm^2 of surface area of the electrodes.

3.4. System efficiency of hydrogen production:

Figure (6a, b and c) shows the system efficiency of hydrogen production at different type of water (tap water add 10%wt KOH, sea water and sea water add 10%wt KOH) and at different levels of distance between electrodes (3, 2 and 1 mm) with 250 cm^2 of surface area of the electrodes during the test. The system efficiency of hydrogen production was ranged from 50.6 to 57.8, 40.7 to 57.8 and 48.7 to 54.5 % for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH, respectively. The results refers that, the highest value of the system efficiency of hydrogen

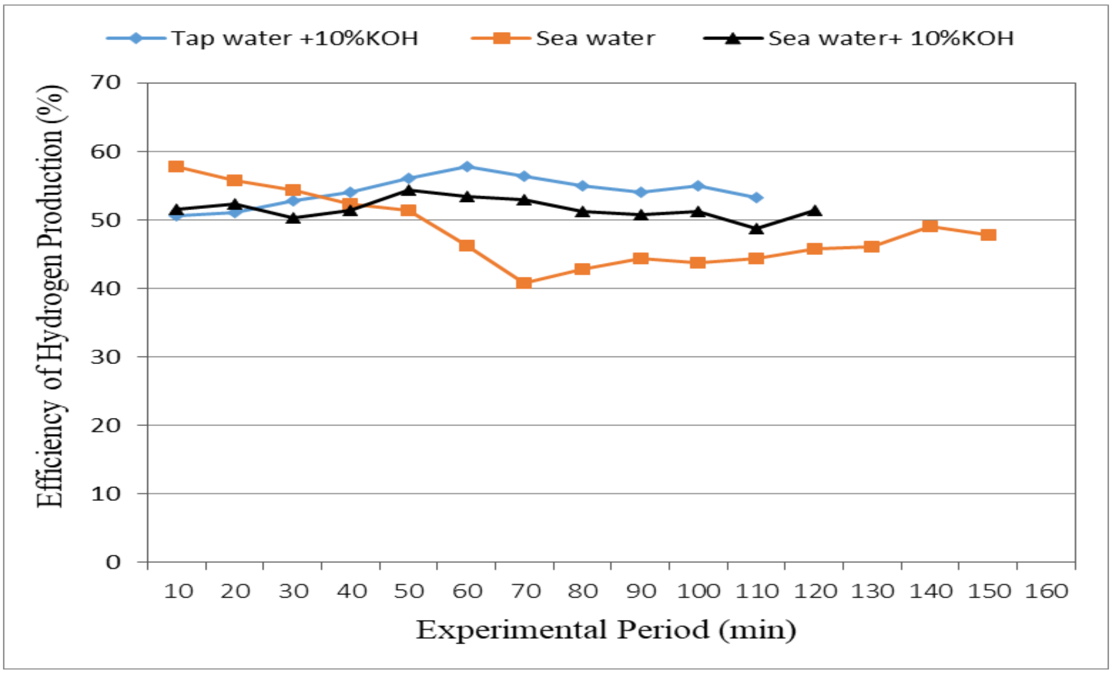

Fig. (6a): The system efficiency of hydrogen production at different type of water at third level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

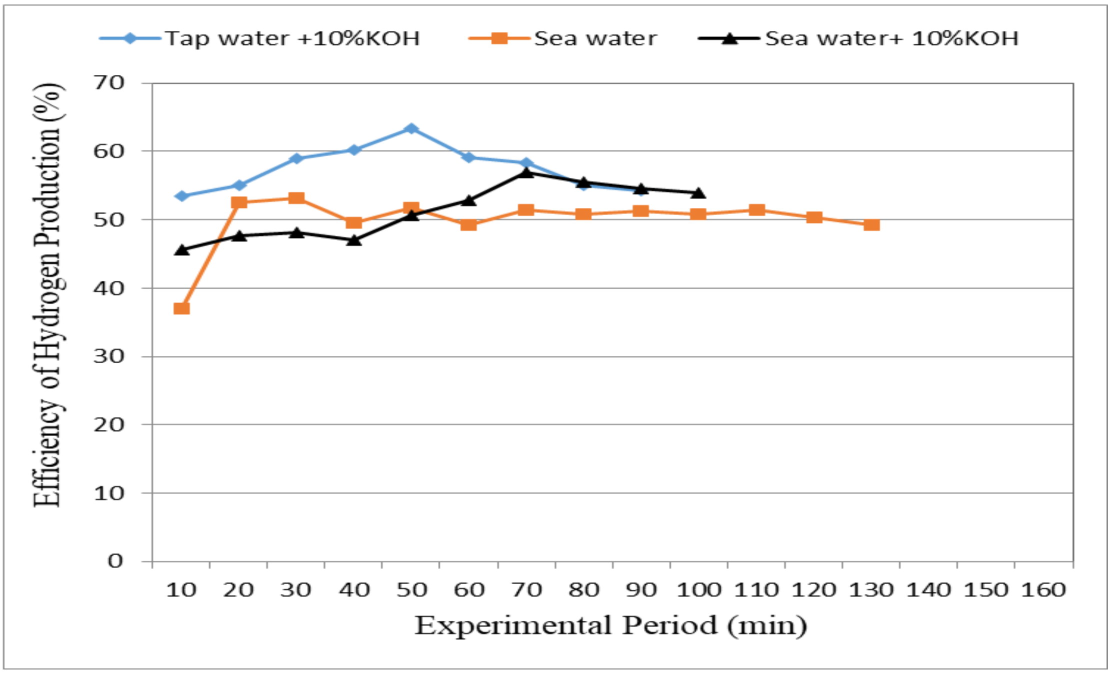

Fig. (6b): The efficiency of hydrogen production at different type of water at second level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

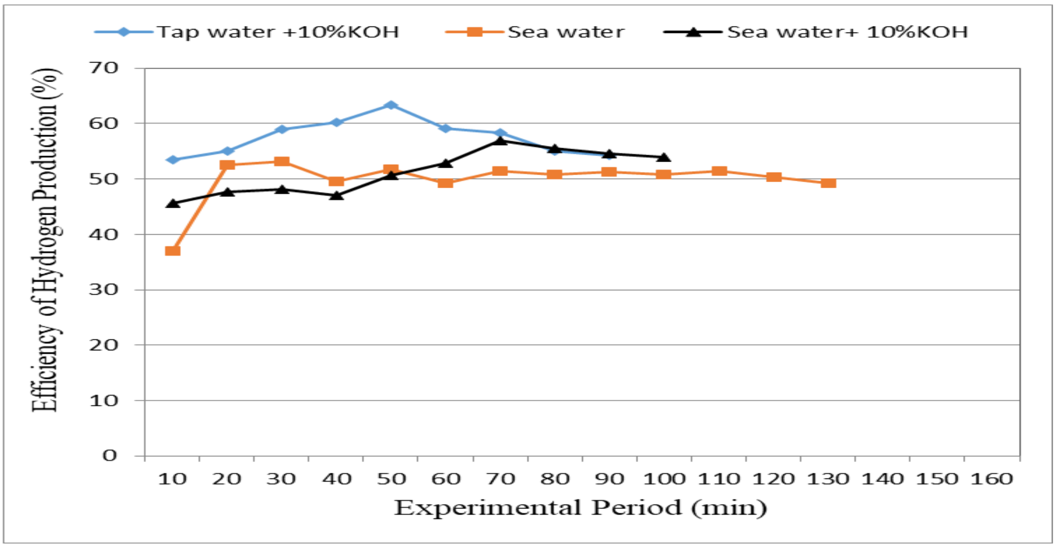

Fig. (6c): The efficiency of hydrogen production at different type of water at first level of distance between electrodes with 250 cm^2 of surface area of the electrodes.

production (57.8 %) was found with the tap water add 10%wt KOH and sea water. While, the lowest value of the efficiency of hydrogen production (40.7) was found with the sea water.

For second level of distance between electrodes, the result refers that, the efficiency of hydrogen production was ranged from 51.7 to 59.7, 43.7 to 53.6 and 52.0 to 57.8 % for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH, respectively. For first level of distance between electrodes, the result refers that, the efficiency of hydrogen production was ranged from 53.5 to 63.4, 37.0 to 53.2 and 45.6 to 57.0 % for tap water add 10%wt KOH, sea water, sea water add 10%wt KOH, respectively.

3.5. Total costs:

Figure (7) shows the total costs of hydrogen production unit at different type of water (tap water add

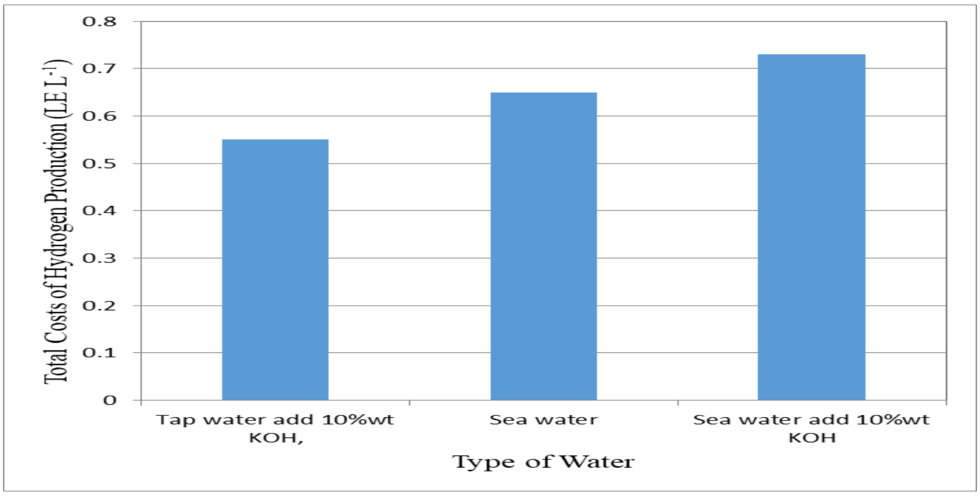

Fig. (7): Total costs of hydrogen production unit for different types of water used.

10%wt KOH, sea water and sea water add 10%wt KOH at the end of experimental period. The results indicate that, the total costs of hydrogen production were 0.55, 0.65 and 0.73 L.E L^{-1} for tap water add 10%wt KOH, sea water and sea water add 10%wt KOH, respectively. The highest value of the total costs of hydrogen production (0.73 L.E L^{-1}) was found with the sea water add 10%wt KOH. While, the lowest value of the total costs of hydrogen production (0.55 L.E L^{-1} W h) was found with the tap water add 10%wt KOH.

Conclusion:

This study was carried out to improve hydrogen productivity at the lowest costs through developing. a simplified unit of water electrolysis. The treatment under study were three type of water (tap water add 10%wt KOH, sea water and sea water add 10%wt KOH) and three distance between electrodes (3, 2 and 1 mm). The obtained results can be summarized as follows:

- The highest value of the energy requirement of hydrogen production (126 W h) was resulted with the sea water for 1 mm distance between electrodes. While, the lowest value of the energy requirement of hydrogen production (86 W h) was obtained with the sea water for 1 mm distance between electrodes.

- The highest value of the produced energy of water (254 W h) was found with the sea water add 10%wt KOH for 1 mm distance between electrodes. While, the lowest value of the produced energy of water (204 W h) was found with the sea water for 3 mm distance between electrodes.
- The highest value of the produced hydrogen of water (64 W h^{-1}) was found with the tap water add 10%wt KOH for 1 mm distance between electrodes. While, the lowest value of the produced hydrogen of water (23 L h^{-1}) was found with the sea water for 3 mm distance between electrodes.
- The total costs of hydrogen production were 0.55, 0.65 and 0.73 L.E L^{-1} for tap water add 10%wt KOH, sea water and sea water add 10%wt KOH, respectively.

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