Study the performance and behavior of the hybrid system

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ABSTRACT

The hybrid power generation system is considered one of the cleanest technologies to generate energy, environmentally friendly and does not emit any pollutants. The hybrid system is a mixture of renewable energy sources, as it consists of the two most important sources of renewable energy, solar or wind energy and hydrogen energy. The hydrogen gas production by alkaline electrolysis cell is one of the cleanest methods, the fuel cell (PEM) type is a clean device that generates energy by using hydrogen gas as a main fuel and is considered an environmentally friendly device that only produces pure water and heat. Preparing an accurate mathematical model is an important process to study the behavior of this system and how it works. The performance of system has been studied by operating it with different loads of current density, the modeling process showed satisfactory results. The operating process of system at different temperatures showed good results and clear improvements in system behavior, the operating power of the alkaline electrolysis cell decreases with increasing temperature, because the temperature effects on the reverse and activation voltage when the process of breaking the covalent bond to split the water molecule, the power of fuel cell is increases with increase the temperature. The pressure improves the performance of the both cells but not significantly and with small values, the voltage and power of the both cells is increases with increasing the value of the operating pressure, but this increase is considered very small. However, the system must not be operated at temperatures higher than (95℃) in order to preserve the manufacturing materials of the both cells. Also, keeping the amount of water in the alkaline electrolysis cell from reaching the steam stage, and keep the humidity of electrolyte membrane and the operating life of the fuel cell.

Keywords: Renewable energy, the hybrid system, Alkaline electrolysis, PEM fuel cell, Study the performance.

1 Introduction

Energy in the world today has become an important priority, as energy is the main axis of the world. The world cannot be imagined without any type of energy, for a simple example the sunlight is considered a type of energy. The impossible thing is live on planet Earth without the light energy of the sun and impossible to do any simple work without consuming some amount of energy. Energy is divided into two main types, traditional (non renewable) and renewable energy. Oil, gas and coal are traditional energy sources these sources have been used for several years as a main source of energy, and they have proven extremely dangerous and seriously harmful to the components of the world, such as humans, animals and plants because these sources of energy emit high amounts of pollution, fumes and harmful emissions and when the harm and danger became clear and threatening the world, and researchers began to notice a large amounts of pollution and huge statistics. In this way, it became necessary to go to sources of energy production safer and more secure. Renewable energy sources have achieved very satisfactory results in terms of safety and environmental protection, and have proven their complete environmental friendliness and protection to the world. Scientific research has proven over the years the effectiveness of renewable energy in protecting the world as it does not emit any pollutant, harmful gases or fumes during the process of operation, production and consumption. Renewable energy types include solar energy, dams, wind and hydrogen energy but these sources are not without disadvantage like other sources due the interruption of these sources from time to time, such as solar energy when clouds are formed. Also, some countries do not have these sources, such as wind energy, as some countries have little to no winds, but some renewable resources may be available at all times, through some operational and design techniques, for example, hydrogen energy is considered a smooth energy and easy to use.

The hydrogen element is a good carrier of electrical energy cause atom of hydrogen carries two electrons, the molecular hydrogen element is not available in nature, hydrogen can be produced using several processes, including thermal and electrical, but thermal processes result in polluting carbon compounds, this part has been excluded in energy production processes such as conventional energy [5], but electrical processes such as electrolysis of the water element do not produce pollutants or gases, only the water is splitting to primary compounds which are hydrogen and oxygen gas by breaking the covalent bond by electric current. The splitting process is done by the alkaline electrolysis cell then the produced gas is collected and stored in the storage cylinder. The hydrogen gas produced by the electrolysis process is used to generate electrical energy by the hydrogen fuel cell, an integrated device is designed to produce hydrogen and use it to produce energy called direct coupling advanced alkaline electrolysis and fuel cells system where the design was very satisfactory and the operational results were homogeneous and close between the units of the system to work as one unit for the production and generation of power [6].

In this paper, the system will be operated on different operating parameters and monitor the system performance and operational behavior in terms of the energy produced.

2 Previous Literature

The researchers proposed the design of an integrated system that combines solar energy and hydrogen energy to generate electrical energy, also achieving the cost for this system. As this system consists of solar panels (photoelectric), battery, alkaline electrolysis, hydrogen storage system and proton exchange membrane fuel cell. The aim of this study was to design and implement this system, as it is considered an independent power system for homes, in order to overcome the need to connect to the electrical network. Also, the effect of the pressure and the operating temperature of the system was studied, the Nernst voltage increases with increasing the pressure of the cell, as for the electrical efficiency increases with increasing pressure. As for the temperature has a negative effect on the Nernst voltage, as the Nernst voltage decreases with increasing temperature, as for the current density, increasing the current density increases the losses in the cell [12].

The clean, environmentally friendly device has been designed that integrates renewable energy sources, this system relies on hydrogen energy as a basic fuel which is producing by alkaline electrolysis cell when the electric current is passing from wind or solar energy, and then generate the electrical energy by injecting the hydrogen produced into the proton exchange membrane fuel cell, this technology is considered useful because of the problems faced by renewable energy sources such as solar energy and wind, including the weather and the lack of availability of these sources. The simulations result show that, the voltage of alkaline electrolysis is higher than the fuel cell, the electrolysis cell does not need to inject more water, only the water generated from the fuel cell and is injected to electrolysis. In this research paper, this system will be developed by studying the effect of temperature and operating pressure of the system [6].

3 Materials and Methods

3.1 The Hybrid System

Renewable energy sources are widely available in terms of scientific research, technical development and in energy generation processes. Solar and wind energy are the most important of these sources, as these sources are more abundant and have achieved clear development and technical progress during the last few years. However, this sources are exposed to some operational problems and difficulties, such as bad weather. Thus, electricity generation is variable in operational times and inability to meet the required load during a period of low available resources, it is appropriate to overcome such difficulties and problems the generated energy was stored in the battery. However, batteries have problems and disadvantage, including short battery life, problems related to storage depth, and also lose their storage content quickly [7].

Therefore, it is better to search for other ways in renewable energy sources to store the generated energy, the technique of combining renewable energy sources is considered one of the most successful methods, such as combining solar energy with hydrogen energy.

The Hydrogen molecule does not exist in nature independently, but combines with other elements, the hydrogen gas can produced by clean technologies such as electrolysis process. Hydrogen gas is produced by the alkaline electrolysis cell and utilizing it by storing it in cylinders and then injecting it into the hydrogen fuel cell to produce energy according to the required power at the appropriate time. This technology is called a hybrid system and was designed in the previous research paper [6].

The hybrid system consists of two basic units, which are the gas production unit (alkaline electrolysis cell) and the electrical power production unit (fuel cell) as shown in Figure .1.

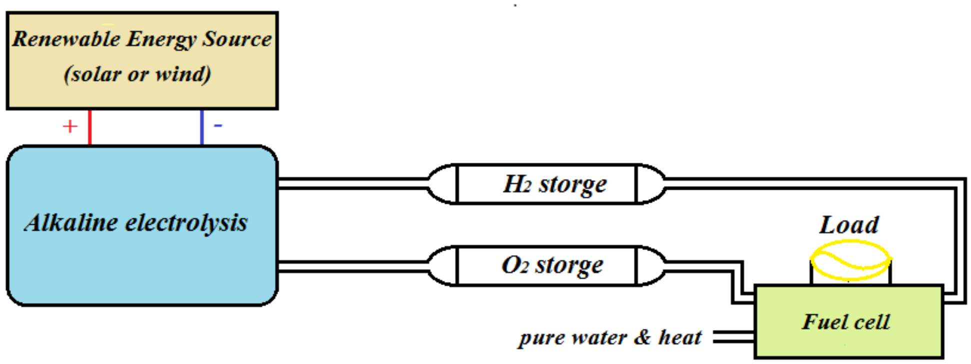

Figure.1. The layout of hybrid system.

The alkaline electrolysis cell requires an electrical current which is generated by a renewable energy source (solar or wind energy) to produce hydrogen gas, then the hydrogen gas that was produced is pumped into the fuel cell to produce the electrical energy at the required power and at the right time.

3.2. Alkaline Electrolysis Cell

Alkaline electrolysis cell consists of several metal chips connected together, these chips are divided into two important parts, the cathode and the anode. The two electrodes are immersed in a conducting electrolyte solution as shown in Figure .2. the electrodes of the alkaline electrolysis cell are connected to a direct current (DC). Electrons pass from the negative electrode through the cathode, where hydrogen atoms form on the cathode as a result of the consumption of hydrogen ions (protons) and the hydroxide ions move towards the anode of the cell. The two compartments are separated by a diaphragm, the produced gas is received by gas collector [8].

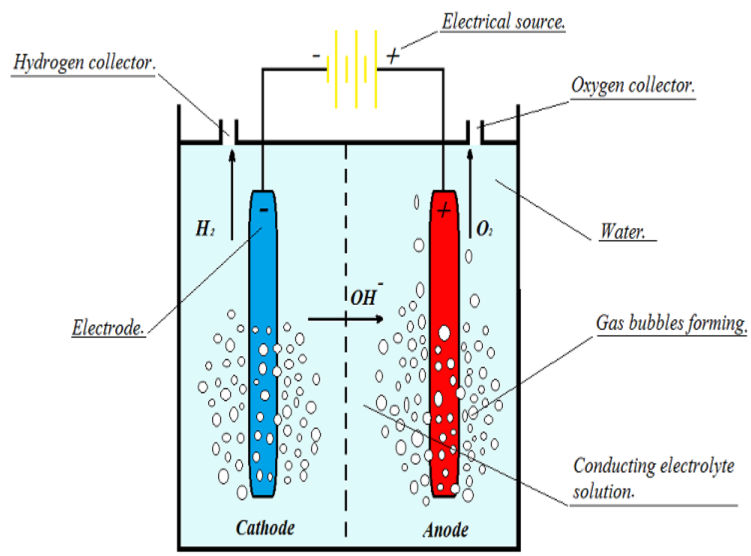

Figure.2. Alkaline electrolysis cell.

3.3. PEM Fuel Cell

Fuel cell is a device that converts the chemical energy in a chemical reaction into electrical energy through a set of reactions which is occur inside the fuel cell, hydrogen gas is the main fuel for the fuel cell. The fuel cell consists of two main electrodes, the cathode and the anode, and the electrolytes are between them. The Catalysts are placed between the electrolyte and the electrodes, hydrogen gas is pumped at the anode and oxygen gas at the cathode as showing in figure .3.

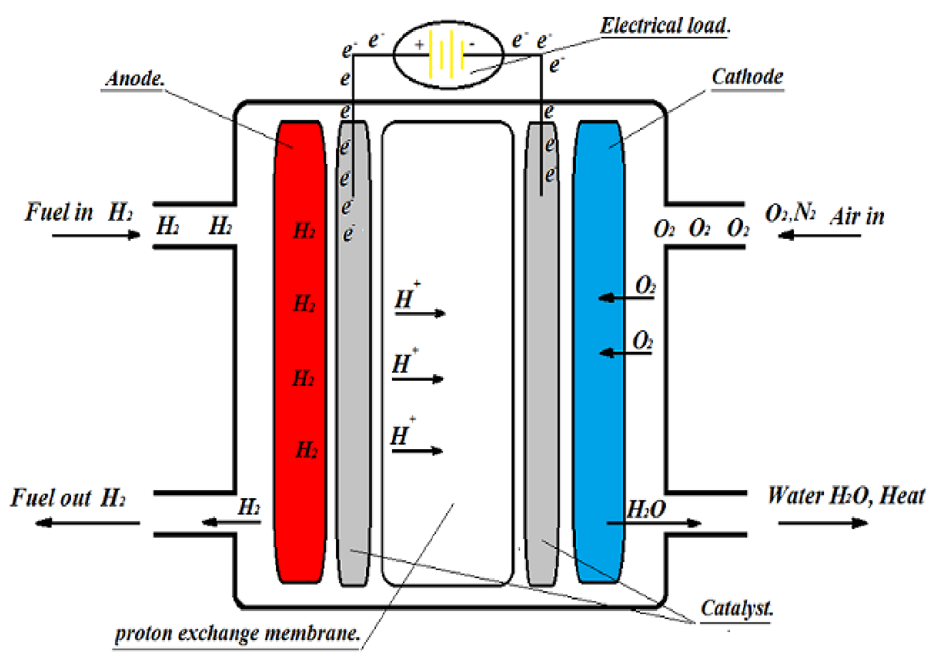

Figure.3. PEM fuel cell

The ions pass through the electrolyte to cross into the cathode, and does not allow electrons to pass through it. Thus, electrons pass to the external electrical wire (electrical load), after the occurrence of the processes and chemical reactions, the cell outputs are pure water and heat [9].

4 The Mathematical Model of System

A system is an assembly unit of components with each other, the system's function is to make a custom function or process under a specific behaviour, the system is described by the mathematical model known as the mathematical concept. Mathematical model is developed by mathematical modelling. The modelling is defined as the writing of equations to describe the mode of a system. The mathematical model is used to predict the behaviour of the system and its mechanism of work so the mathematical model must be more accurate. Preparing an accurate mathematical model of the system is done by using a computer simulation program to perform difficult mathematical operations and many calculations. The computer simulation program allows the system to run with many parameters and different values [1].

4.1 Alkaline electrolysis model description

The description of the system dynamically and mathematically depends on preparing an integrated mathematical model for the alkaline electrolysis cell. The model also describes the processes that occur within the system, including the thermodynamic and electrochemical sides. The general electrochemical reaction of electrolysis [10]:

$$H_2O_{(liquid)} + DC\ current\ \rightarrow H_{2_{(g)}} + \frac{1}{2}O_{2_{(g)}} \tag{1}$$

1. Hydrogen evolution reaction (HER)

$$H_2O_{liquid} + 2e^- \rightarrow H_{2_{(g)}} + 2OH^- \tag{2}$$

2. Oxygen evolution reaction (OER)

$$2OH^- \rightarrow \frac{1}{2}O_{2_{(g)}} + H_2O + 2e^- \tag{3}$$

The reversible voltage It can be said that the maximum possible useful work of the electrolysis (reversible work) [2], and can be calculated by following formula [11]:

$$V_{rev} = V_{rev}(T) + \frac{R\cdot T}{z\cdot F} ln\frac{(P-P_{KOH})^{1.5}\cdot P_w}{P_{KOH}} \tag{4}$$

$$V_{rev}(T) = 1.5184 - 1.5421e^{-3}\cdot T + 9.523e^{-5}\cdot\ T\cdot ln\,T + 9.84e^{-8}\cdot T^2 \tag{5}$$

Where P_W is the vapour pressure of a purified water, P_{KOH} the vapour pressure of the electrolyte solution in the (atm) unit, R gas constant 8.314 ($J/mol\cdot K$), F Faraday constant 96485 coulombs, T the temperature of electrolysis cell (K), z the number of electrons in reaction. The voltage of alkaline water electrolysis cell can be expressed in the following relationship [11]:

$$V_{cell} = V_{rev} + V_{act} + V_{ohm} \tag{6}$$

The activation voltage required for the electrochemical reaction, it is also a measure of the extent of the electrode activity of the electrolysis cell [11], Can be calculated by the following formula:

$$V_{act} = 2.3026 \frac{R \cdot T}{z \cdot F \cdot \alpha_{a/c}} \log(\frac{i}{i_o}) \quad (7)$$

Where the $\alpha_{a/c}$ is the charge transfer coefficient of the electrodes, i_o the exchange current density (A/cm^2).

The ohmic voltage of the alkaline electrolysis cell occur as a result of the ohmic losses due to the flow of electrons on the surface of the electrodes and conductors of the alkaline electrolysis cell, and V_{ohm} is given by:

$$V_{ohm} = r \cdot i \quad (8)$$

$$r = \frac{\delta}{\sigma_\varepsilon} \quad (9)$$

$$\sigma_\varepsilon = \sigma_o(1-\varepsilon)^{1.5} \quad (10)$$

δ The electrolyte thickness (cm), σ_o the conductivity of KOH solution (S/cm), σ_ε the electrical conductivity in the presence of bubbles and ε the void fraction of the electrolyte.

The electrolysis power can be calculated by the following law, which is multiplying the electric current by the electrolysis voltage.

$$Power_{electrolysis} = \left(\frac{i_{FC}}{A}\right) \cdot V_{cell} \quad (11)$$

4.2. PEM Fuel Cell Model Description

Fuel cell modeling is one of the most important processes for obtaining a suitable design for the cell, as developers work to improve the process of designing and manufacturing a fuel cell by preparing an accurate and robust mathematical model that predicts the performance of the fuel cell under a wide range of operating conditions. The model also finds and solves fuel cell problems. The mathematical model illustrates the most important sides of the cell, the thermodynamic and the electrochemical side by showing the chemical equations and electrical laws of the cell [4].

1. The general electrochemical reaction of PEM fuel cell:

$$H_{2(g)} + \frac{1}{2} O_{2(g)} \rightarrow H_2O_{(liquid)} + Electric\ power + Heat \quad (12)$$

2. The anode side:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (13)$$

3. The cathode side:

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (14)$$

The electrical model of fuel cell describes the electrical behavior, such as electric current and potential difference, where the cell voltage can be calculated by the following law:

$$V_{Cell} = E - V_{act} - V_{ohm} - V_{conc} \quad (15)$$

Where E the reversible voltage of cell is 1.229 V at standard operating conditions 1 bar and 25℃, and V_{act} the activation voltage of the cell that is occurs due the activation energy when a chemical reaction is start. It can be calculated using the following law [3]:

$$E = 1.229 - 0.85 \cdot 10^{-3}(T - 298.15) + 4.3085 \cdot 10^{-5} \cdot T \cdot \ln[\frac{P_{H_2} \cdot P_{O_2}{}^{0.5}}{P_{H_2O}}] \quad (16)$$

Where T the temperature of cell (K), P_{H_2} pressure of fuel, P_{O_2} pressure of oxidant, P_{H_2O} pressure one mole of water.

$$V_{act} = -\xi_1 + \zeta_2 \cdot T + \xi_3 \cdot T \cdot \ln(C_{O_2}) + \zeta_4 \cdot T \cdot \ln(\mathrm{i_{FC}}) \quad (17)$$

Where ξ_i are parametric coefficients, $\mathrm{i_{FC}}$ is the cell current (A) C_{O_2} the concentration of oxygen gas (mol/cm^3) can be found in the following equation [3]:

$$C_{O_2} = \frac{P_{O_2}}{(5.08 \cdot 10^{-5} \cdot \exp^{(\frac{-498}{T})})} \quad (18)$$

The ohmic voltage of the cell occurs as a result of ohmic losses due to the passage of electrons through the electrical wires and conductors between the two electrodes, the ohmic voltage value is estimated by the following law:

$$V_{ohm} = i_{FC}(R_m + R_c) \quad (19)$$

Where R_c is the constant part of cell's resistance, and R_m depends on the temperature and on a parameter Ψ which represents membrane hydration level (takes the value 14 if the membrane is fully hydrated and 23 if the membrane is over saturated), and R_m is given by:

$$R_m = \frac{\rho_m \cdot l}{A} \quad (20)$$

Where l is the membrane thickness, A the cell active area (cm^2), ρ_m specific membrane resistance ($\Omega \cdot$ cm) and estimated by the following law [3]:

$$\rho_m = \frac{(181.6 \cdot [1+0.03 \cdot \left(\frac{i_{FC}}{A}\right) + 0.062 \cdot (\frac{T}{303})^2 \cdot (\frac{i_{FC}}{A})^{2.5}])}{(\left[\Psi - 0.364 - 3 \cdot (\frac{i_{FC}}{A})\right] * exp^{\left(\frac{4.18 \cdot (T-303)}{T}\right)})} \quad (21)$$

The concentration voltage of the cell occurs as a result of the excess reactive concentration near the catalyst surfaces, where B is parameter that depends on the type of fuel cell, and can be calculated by using following law:

$$V_{conc} = -B \cdot \ln(1 - \frac{i}{i_L}) \quad (22)$$

The cell power can be calculated by the following law, which is multiplying the electric current by the cell voltage.

$$Power_{fuel\ Cell} = \left(\frac{i_{FC}}{A}\right) \cdot V_{cell} \quad (23)$$

Table 1: *Setting parameters of alkaline electrolysis [6].*

Constant parameter	Symbol	Value
Area of electrodes	A	475 cm2
Faraday's constant	F	96485 C/mole

Number of cells	n_c	36
Number of electrons	z	2
Gas constant	R	8.314 J/mole*K
exchange current density	i_o	30 A/cm2

Table 2: *Setting parameters of PEM fuel cell [3].*

Parameter	Value	Parameter	Value
T	343 K	B	0.016
A	50.6 cm2	ξ_1	-0.948
L	178 μm	ξ_2	$2.86 \cdot 10^{-3} + 2 \cdot 10^{-4} \ln(A) + 4.3810 \cdot 10^{-5} \ln(C_{H_2})$
P_{H_2}	1 atm	ξ_3	$7.6 \cdot 10^{-5}$
P_{O_2}	1 atm	ξ_4	$-1.93 \cdot 10^{-4}$
P_{H_2O}	1 atm	Ψ	23
R_c	0.0003 Ω	i_L	1.5 $\frac{A}{cm^2}$

5 Results and Discussion

5.1. The Model Validation

In this paper, a hybrid system for clean energy generation was modeled, as this system includes two basic units, a hydrogen gas generation unit (alkaline electrolysis cell) and a power generation unit (fuel cell), The system was operated on different loads of current density and different parameters, The aim of this study was to design an accurate model for this system, and then operate it in a correct and smooth way. Also, monitor system behavior when operating loads change and note the results of both units.

The results were very satisfactory as they were presented in the previous research paper, due to the same approach followed [6]. The system was developed in this research paper by applying different equations for the fuel cell. The results obtained were compared with research papers to ensure the validity of the results that prove the validity of the modeling and compensation [11] [3].

However, in this paper the focus was on other operational parameters such as temperature and pressure, which is very important to clearly predict the behavior of the system. The change in the performance of the both cells was very clear as a result of the change of the operational parameters, as the operating temperature had a significant effect on the cell voltage and power. As for the operational pressure does not have a significant effect on cell performance.

5.2. (I-V) Characteristics of Units

The curve of current and voltage (I-V) characteristics is one of the most important results that must be obtained to evaluate the model being designed, the cells voltage is one of the most important parameters, which is affected by several operational factors such as temperature, operating pressure and current density. The voltage results of both cells are different in terms of values as showing in figure .4, as the value of the current density increases, the voltage value of the alkaline electrolysis cell increases and the voltage of the fuel cell decreases due to the difference in the nature of the chemical reaction in both cells, where the chemical reaction in the alkaline electrolysis cell need a large amount of energy to break the covalent bond between the hydrogen and oxygen atom.

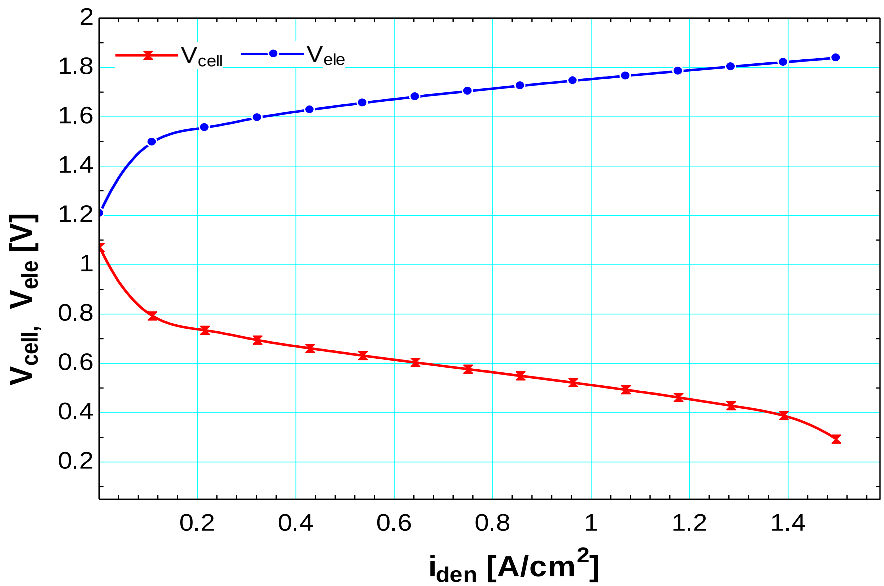

Figure.4. The system voltage changes with the change in the current density.

5.3. The Operating Temperature Effect on Electrolysis Cell Parameters

- **The Power and Voltage of Electrolysis Cell**

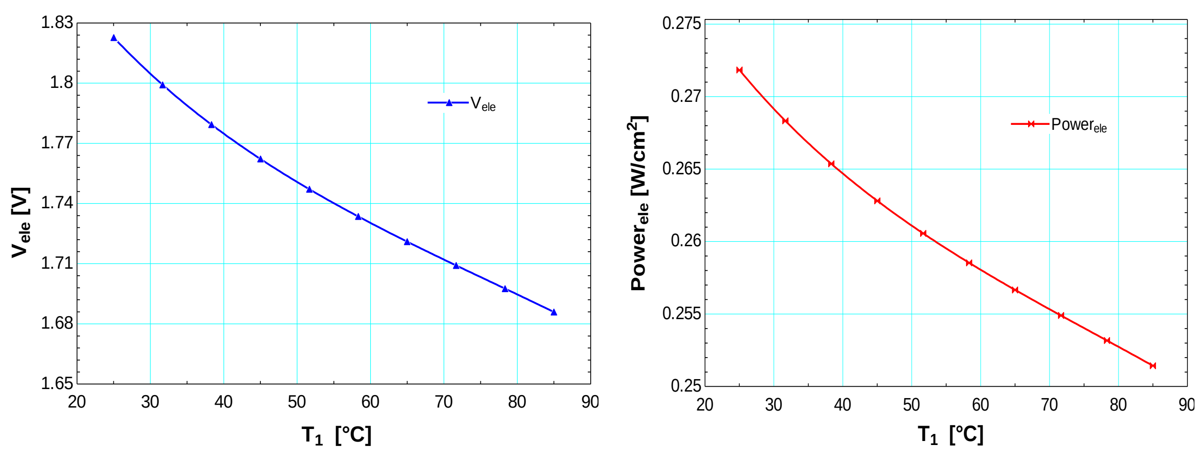

Figure.5. The temperature effect on the voltage and power of alkaline electrolysis.

The effect of temperature on the power and voltage of the fuel cell is very clear, the alkaline electrolysis voltage decreases when the operating temperature increases as showing in figure.5, that the voltage of the alkaline electrolysis cell is a function of temperature such as the reverse voltage and the activation voltage as noted in equation 4, 5, 6. The temperature change affects the water molecules and the covalent bond of their atoms. Thus, the process of break the covalent bond of water molecules will be easy.

5.4. The Operating Pressure Effect on Electrolysis Cell Performance

- **The Power and Voltage of Electrolysis Cell**

As showing in Figure. 6, the value of voltage and the power of the alkaline electrolysis cell increases with the increase in the operating pressure, but this performance improves only slightly and by small values. However, it is better not to operate the cell with more pressure than the allowable values, in order to preserve the electrolysis mechanism and operation life.

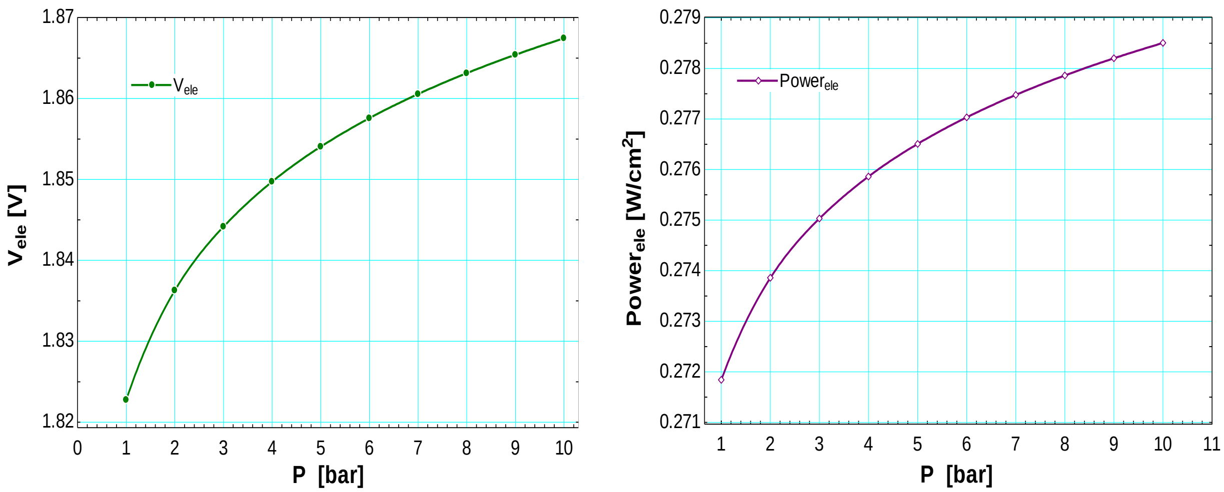

Figure.6. The pressure effect on the voltage and power of alkaline electrolysis.

5.5. The Operating Temperature Effect on Fuel Cell Parameters

- **The Power and Voltage of Fuel Cell**

The performance of the fuel cell is clearly affected by the change in the operating temperature, unlike the effect in alkaline electrolysis cell. The curve in Figure 7 illustrates the relationship between the change of operating temperature and cell performance (voltage and power), the cell performance increases with increasing cell temperature, and the performance improves significantly, it is possible to improve the performance of the cell by increasing the temperature, but the cell cannot be operated at the temperature (95 ℃) or more to run the fuel cell in a safe state, that to keep the humidity of electrolyte membrane and the operating life of the fuel cell.

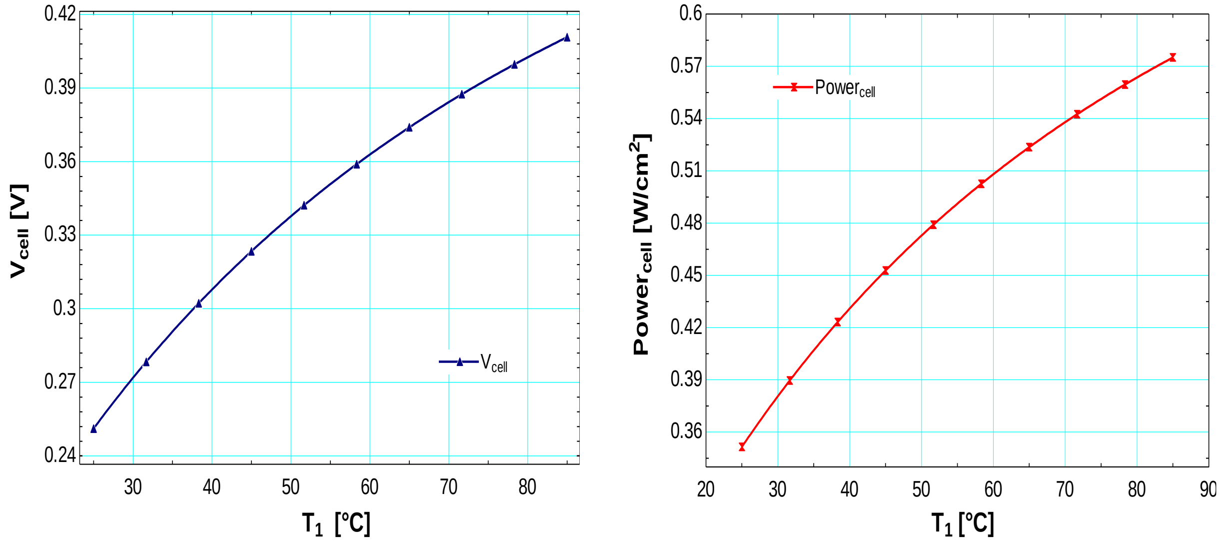

Figure.7. The temperature effect on the voltage and power of fuel cell.

5.6. The Operating Pressure Effect on Fuel Cell Parameters

- **The Power and Voltage of Fuel Cell**

The operating pressure of the fuel cell is one of the parameters that improve the performance of the cell but not significantly as shown in figure 8, unlike the effect of temperature.

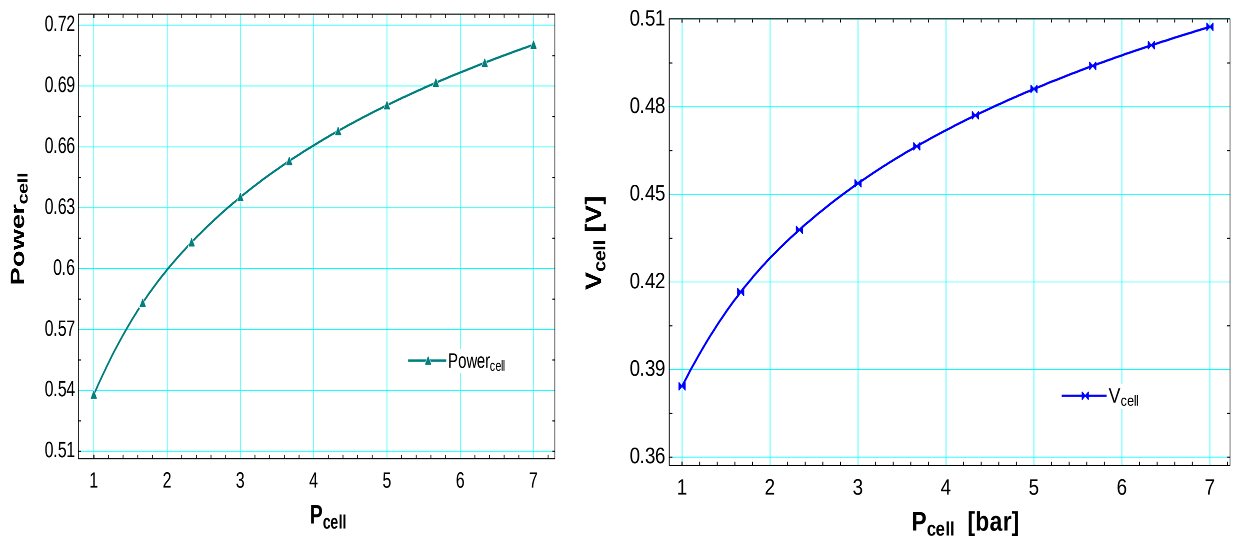

Figure.8. The pressure effect on the voltage and power of fuel cell

6 Conclusions

The renewable energy sources are very clean sources and do not produce any harmful carbon emissions or polluting fumes. However, some of these clean sources face difficulties and problems during power generation and transmission processes, it was necessary to focus on

integrating two sources of renewable energy to overcome these difficulties. Solar and hydrogen energy are among the best renewable energy sources, a device consisting of two basic units has been designed as the alkaline electrolysis cell and the fuel cell called the hybrid system.
In this paper, a mathematical model for this system is designed and then the system is operated on different loads of current density. Also, making improvements to the system's performance and studying its operational behavior in terms of the generated voltage and the power produced by operating the system at different temperatures and pressures.
The results showed that the voltage of the alkaline electrolysis cell is $V_{ele} = 1.82\ V$ at the current density $i_{ele} = 0.14\ \frac{A}{cm^2}$, and the voltage of the fuel cell is $V_{fuel\ cell} = 0.38\ V$ at the current density $i_{fuel\ cell} = 1.4\ \frac{A}{cm^2}$. The process of operating the system at different temperatures showed good results and clear improvements in system behavior, the operating power of the alkaline electrolysis cell decreases with increasing temperature, because the temperature effects on the reverse and activation voltage when the process of breaking the covalent bond to split the water molecule occurs during the reaction, as the power of fuel cell is increases with increase in the operating temperature, and the cell performance improves significantly. However, the system must not be operated at temperatures higher than (95℃) in order to preserve the manufacturing materials of the both cells. Also, keeping the amount of water in the alkaline electrolysis cell from reaching the steam stage, and keep the humidity of electrolyte membrane and the operating life of the fuel cell. The operating pressure improves the performance of the both cells but not significantly and with small values.

7 Acknowledgment

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