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Integrated PEM Electrolysis–Fuel Cell and (LiBr–H_2O) Absorption Refrigeration System

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Abstract:
The current research presents a renewable energy technology related to hydrogen fuel and its optimal utilization; the EES simulation software was used to study each unit of the system. An electrolysis cell is used to produce hydrogen, which is then injected into a (PEM) fuel cell is used to produces electrical power, pure water, and a quantity of heat in the exhaust. This heat is then injected into an absorption refrigeration system (LiBr–H_2O) type for cooling purposes. The results showed that the best operating conditions were at (90 °C), with a cooling temperature of (7 °C). The voltage of PEM fuel cell was (0.46 V) and electrolysis cell (1.83 V), and the power output of the fuel cell was (0.6464 W) and the electrolysis (1.101 W). The coefficient of performance for the absorption refrigeration system was very good, approximately (0.7185), The findings demonstrate that integrating hydrogen energy systems with absorption cooling significantly enhances overall energy utilization and system efficiency.
Keywords: The PEM fuel cell, The absorption refrigeration system, Bromide lithium (LiBr-H_2O), The Hybrid Cooling System.

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دمج نظام التحليل الكهربائي وخلية الوقود نوع (PEM) بنظام التبريد بالامتصاص نوع بروميد الليثيوم (LiBr–H_2O)

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الملخص:

في هذا البحث تم عرض أحد تقنيات الطاقة المتجددة المتعلقة بوقود الهيدروجين مع إمكانية الإستفادة المثلى منها، حيث تم إستخدام برنامج المحاكاة (EES software) لدراسة كل وحدة من النظام. يتم استخدام خلية التحليل الكهرومائي لإنتاج الهيدروجين ومن ثم حقنه لخلية الوقود الهيدروجينية نوع (PEM) حيث تقوم بإنتاج القدرة الكهربائية والماء النقي وكمية من الحرارة في العادم، سيتم حقن هذه الحرارة لنظام التبريد بالامتصاص نوع بروميد الليثيوم (LiBr–H_2O) للإستفادة منه في مجال التبريد. أظهرت النتائج ان أفضل الظروف التشغيلية كانت عند درجة حرارة (90 °C) حيث كانت درجة حرارة التبريد (7°C) حيث كان فرق الجهد لكل من خلية الوقود الهيدروجينية (0.46 V) وخلية التحليل الكهرومائي (1.83 V) والقدرة المنتجة لخلية الوقود الهيدروجينية (0.6464 W) وخلية التحليل الكهرومائي (1.101 W)، وكان معامل الاداء لدورة التبريد جيد جدا حوالي (0.7185)، تُظهر النتائج أن دمج أنظمة طاقة الهيدروجين مع التبريد بالامتصاص يعزز بشكل كبير الاستخدام الكلي للطاقة وكفاءة النظام.

الكلمات الدالة: خلية الوقود نوع (PEM)، نظام التبريد بالامتصاص، محلول بروميد الليثيوم (LiBr–H_2O)، نظام التبريد الهجين.

Introduction:

Energy production processes around the world today are increasing significantly and noticeably. However, a large proportion of its sources are considered unclean or not environmentally friendly, which in turn causes problems for the world such as environmental pollution, fumes, and toxic gases. Consequently, many research studies have begun to focus on the clean side of energy generation, represented by renewable sources.

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This research focuses on hydrogen energy, which is used to generate electrical power by hydrogen fuel cells. Hydrogen energy has an advantage over other renewable energy sources, such as solar and wind power, due to its continuous operation and generation reliability. Solar and wind power generation which have intermittent due to several reasons, including weather conditions and the suitability of power plant locations. Furthermore, their productivity is limited, because generated energy can only be transmitted or stored via battery systems (Xinyuan Cao, 2024). These challenges highlight the need to explore more reliable and sustainable renewable energy options. Hydrogen cannot be found alone in nature around us, but it is found combined with several elements, some of which are clean, such as water, and some of which are harmful and polluting, such as carbon compounds such as methane gas, fossil fuels, and biomass (Assia Marghani, 2023).

This research focuses on clean energy fields; therefore, the focus will be on clean hydrogen generation processes. One of the most important processes is the production of hydrogen from pure water, which is called water electrolysis. This process constitutes a fundamental aspect of the transition to clean energy, owing to its advanced development and environmental friendliness. The process of electrolysis of water requires pure water to increase production efficiency and the environmental impact of the process (Arsad S.R, 3, 2024). After hydrogen fuel was produced, and as expected to be a sustainable fuel, hydrogen fuel has gained a very important position in enhancing energy security and economic sustainability. Therefore, it will be exploited in the process of generating electrical energy through electricity generating devices called “hydrogen fuel cells”. Hydrogen fuel is injected into this cell along with oxygen gas present in the air, and the outputs are electrical energy, pure water, and heat from the cell's exhaust (Gaydaa AlZohbi, 8, 2024). To ensure optimal utilization of this system, it will be integrated with an absorption cooling cycle by recovering both the water and the thermal energy released from the fuel cell exhaust. The thermal energy is injected into the generator of the absorption cooling system, so that the heat separates the coolant fluid from the lithium

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bromide salt, and this coolant fluid is used for the required cooling process (M.A. Gadalla, 6, 2010).

In many previous studies, the process of producing electrical energy is done by means of a hydrogen fuel cell by injecting a quantity of hydrogen and oxygen gases, and the outputs are electrical power, pure water, and heat in the cell exhaust. In order to obtain the optimal benefit from the fuel cell, the heat in the cell exhaust was exploited to operate the Absorption refrigeration System of the lithium bromide type ($LiBr–H_2O$), as explained in the previous research (Hamza Ahmed 9, 2022). However, this research study did not include a hydrogen fuel production unit. Therefore, the aim of this research work is to add a (PEM) electrolysis cell unit to produce hydrogen gas by separates hydrogen molecules from oxygen in pure water by passing an electric current through it for injection into a (PEM) hydrogen fuel cell, which produces the electricity power, pure water, and a quantity of heat. After that, the exhaust from this cell is injected into the heat generator of the lithium bromide absorption refrigeration system lithium bromide type ($LiBr–H_2O$). The scientific idea of this research is to prepare a mathematical model for each unit of this system. This model helps in understanding the dynamic and electrical behaviour, and the operation behaviour between the units, and understands the homogeneity between them. Thus, it is an integrated system that generates electricity using hydrogen fuel, and obtains the hydrogen fuel through the (PEM) electrolysis cell. This system is also used in the field of cooling when operating the absorption cooling system, thus increasing the operational efficiency of this system and achieving optimal benefit from its operation.

The integrated system description:

In this research paper, renewable energy sources will be utilized as much as possible to benefit from them in various useful fields, away from polluting sources. This is achieved by integrating several systems together. Hydrogen gas is generated through an electrolysis cell, and then injected into a fuel cell to generate electricity, water, and heat. This water and heat are then used to operate an absorption cooling system. In the first system on the right of the picture, as shown in Figure (1), the hydrogen gas is produced by electrolysis

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process, which is consists of two electrodes (cathode and anode) and the polymer electrolytic membrane between them. As a result of the electrochemical reaction that occurs inside the cell, the water molecule is divided into hydrogen and oxygen gas at the two electrical electrodes. The hydrogen gas is at the cathode electrode and the oxygen gas is at the anode electrode. This splitting and reaction occur after pumping water to the anode side, where it splits into protons (H^+), electrons (e^-), and oxygen (O^2), Since the proton membrane has the property of proton conduction, it allows protons to pass to the other electrode, which is the cathode. Also, the electrons (e^-) move to the cathode side through the external power circuit, which provides the driving force (cell voltage) to react with protons (H^+) which is occurring at the cathode electrode to form hydrogen gas (H2) (S. Shiva Kumar, 2019). After obtaining the required amount of hydrogen fuel to operate the fuel cell, this amount of fuel is injected into the second part of the system as shown in Figure (1) in the middle of the image. A fuel cell is an electrochemical device that converts hydrogen fuel into electrical energy and outputs of this cell is pure water and heat (Benchouia. N, 2013). The advantages of the proton exchange membrane (PEM) fuel cell are low operating temperatures ranging between (70-100°C). These temperatures allow for faster operation (short warm-up time), which increases the resistance of cell materials to corrosion. However, catalysts are required to start the electrochemical process at low temperatures. These catalysts include the use of noble metals (usually platinum). The operating principle of the cell is to inject the produced hydrogen gas into the anode side, so the hydrogen is oxidized and separates into protons and electrons. Because the proton membrane allows the protons to pass through it to the cathode side, it does not allow the electrons to pass because it is not an electronic conductor. Therefore, the electrons move towards the electrical load, and an electric current is generated. Oxygen gas is injected into the cathode side, where it is reduced and reacts with the protons that have crossed the proton membrane to form a water molecule, which is released with the heat of the cell (Leonardo Giorgi, 2013). Fuel cell systems are not primarily used in the thermal field, but the heat from the exhaust is

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a secondary output of the cell. To make the best use of the fuel cell system and increase its efficiency, the heat coming out of the exhaust will be used to operate the absorption cooling system (Nikhil Jain, 2014). An absorption cooling system consists of four main components: the heat generator, the evaporator, the condenser, and the absorber. The absorption cooling system works when the heat generator receives the operating heat from the fuel cell exhaust. This heat separates the water vapour which is the refrigerant, from the lithium bromide salt. The water vapour enters the condenser to condense and is then throttled by a valve, Then enters to the evaporator where cooling is provided. Then the absorber stage where water vapour enters after it has been used to cool the required space, to mix with the lithium bromide salt coming from the thermal generator, repeating this process is the mechanism of the absorption refrigeration cycle (Xiaolin Wang, 2, 2009).

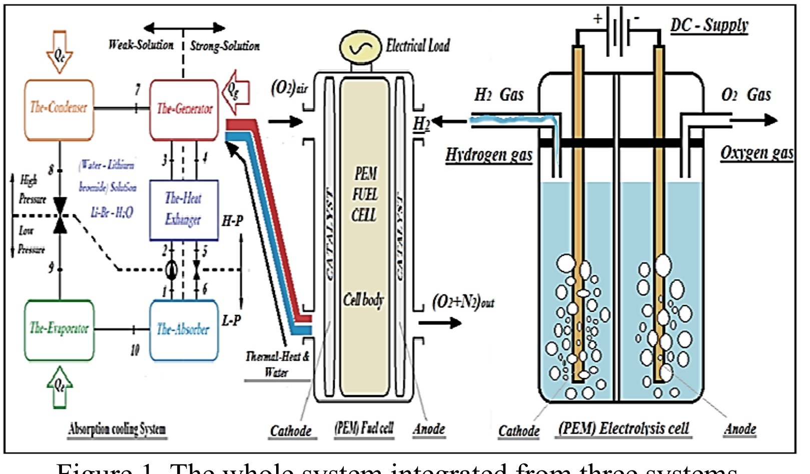

Figure 1. The whole system integrated from three systems.

Mathematical Modelling of the Integrated System:

The mathematical model provides a precise understanding of the dynamic behaviour of the system. A mathematical model will be developed that shows the operating mechanism and basic working principle of each system under study will be developed using several variables, parameters and constants for the three systems shown in Tables 1, 2, and 3, in Engineering equation solver (EES) software.

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This model aims to represent the physical, thermal, and mass relationships between system components, enabling performance analysis under various operating conditions and identifying critical influences that control operational efficiency and stability. This model aims to represent the physical, thermal, and mass relationships between system components, enabling performance analysis under various operating conditions and identifying critical influences that control operational efficiency and stability. This model is also a basic tool for interpreting experimental results, verifying thermal and mass consistency, and guiding design towards more realistic and efficient solutions, in this model several hypotheses were set when creating the programming code for the system, including:

- The pressure losses were ignored, especially in pipes.
- Steady state steady flow in the whole system.
- Heat losses, especially in heat units, were ignored and considered in the ideal case.
- The work pump was ignored because its small value.

1. The PEM electrolysis cell:

- The general reaction of an electrolysis cell:

$$H_2O + \text{ The electrical power } \rightarrow H_2 + \frac{1}{2}O_2 \quad (1)$$

- The voltage of PEM electrolysis:

$$V_{EC} = E + V_{act} + V_{ohm} + V_{conc} \quad (2)$$

- The reversible voltage of an electrolysis cell:

$$E == 1.48 - 0.85 \cdot 10^{-3}(T_{EC} - 298.15) + 4.3085 \cdot 10^{-5} \cdot T_{EC} \cdot \ln\left(\frac{P_{O_2}^{0.5} \cdot P_{H_2}}{P_{H_2O}}\right) \quad (3)$$

- The activation voltage of an electrolysis cell:

$$V_{act} = \frac{R \cdot T_{EC}}{\alpha \cdot n \cdot F} \cdot \ln\left(\frac{i}{i_o}\right) \quad (4)$$

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Wrere (i) is the current density of electrolysis cell, and (i_o) is the exchange current density where this loss becomes zero and is given by

$1.08*10^{-7}*\exp(10.086*T_{EC})$ (A/cm2).

- The ohmic voltage of an electrolysis cell:

$$V_{ohm} = i \cdot \frac{t_{FC}}{\sigma_{mem}} \qquad (5)$$

The (t_{FC}) is membrane's thickness, (σ_{mem}) the conductivity of the membrane and is given by:

$$\sigma_{mem} = (0.005139 \cdot \lambda_{mem} - 0.003260)\left(\exp^{(1268)\left(\frac{1}{303}-\frac{1}{T_{EC}}\right)}\right) \qquad (6)$$

Where (λ_{mem}) represents membrane's hydration and takes the value:

$$\lambda_{mem} = 0.043 + 17.81 \cdot a - 39.85 \cdot a^2 + 36 \cdot a^3 \qquad (7)$$

Where (a) is the membrane water activity, and in a PEM electrolyser the membrane always operates under almost 100% humidification, so a=1.

- The concentration voltage of an electrolysis cell:

$$V_{conc} = -\left(\frac{R \cdot T}{n \cdot F}\right) \cdot \ln(1 - \frac{i}{i_L}) \qquad (8)$$

Where the (i_L) is the maximum current density.

- The power consumed of an electrolysis cell

$$P_{EC} = I \cdot V_{EC} \qquad (9)$$

2. **The PEM fuel cell:**

- The general reaction of a PEM fuel cell:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{ The electrical power} + \text{Heat} \qquad (10)$$

- The voltage of a PEM fuel cell:

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$$V_{FC} = E - V_{act} - V_{ohm} - V_{conc} \tag{11}$$

- The reversible voltage of a PEM fuel cell:

$$E = 1.229 - 0.85 \cdot 10^{-3}(T - 298.15) + 4.3085 \cdot 10^{-5} \cdot T \cdot \ln\left(\frac{P_{O_2}^{0.5} \cdot P_{H_2}^{1}}{P_{H_2O}^{1}}\right) \tag{12}$$

- The activation voltage of a PEM fuel cell:

$$V_{act} = -[F_1 + F_2 \cdot T + F_3 \cdot T \cdot \ln(C_{O_2}) + F_4 \cdot T \cdot \ln(i_{FC})] \tag{13}$$

Where (F_i) are parametric coefficients, (i_{FC}) is the cell current, and (C_{O_2}) is the oxygen's concentration (mol/cm3) on the catalytic interface which equals:

$$C_{O_2} = \frac{P_{O_2}}{5.08 \cdot 10^6 \cdot \exp^{(\frac{-498}{T})}} \tag{14}$$

- The ohmic voltage of a PEM fuel cell:

$$V_{ohm} = i_{FC} \cdot (R_m + R_c) \tag{15}$$

$$R_m = \frac{\rho_m \cdot T_m}{A_{FC}} \tag{16}$$

$$\rho_m = \frac{(181.6 \cdot [1 + 0.03 \cdot \left(\frac{i_{FC}}{A_{FC}}\right) + 0.062 \cdot (\frac{T}{303})^2 \cdot (\frac{i_{FC}}{A_{FC}})^{2.5}])}{([\omega - 0.634 - 3 \cdot (\frac{i_{FC}}{A_{FC}})] \cdot \exp^{[\frac{(4.18) \cdot (T-303)}{T}]})} \tag{17}$$

Where (ω) which represents membrane hydration level (takes the value 14 if the membrane is fully hydrated and 23 if the membrane is over saturated).

- The concentration voltage of a PEM fuel cell:

$$V_{conc} = -B \cdot \ln(1 - \frac{i_{FC}}{i_L}) \tag{18}$$

- The power consumed of a PEM fuel cell:

$$P_{FC} = I \cdot V_{FC} \tag{19}$$

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3. The Absorption refrigeration system

By applying the first law of thermodynamics to every unit:

- The absorber.

The Energy balance:

$$Q_a = (m_{10} \cdot h_{10}) + (m_6 \cdot h_6) - (m_1 \cdot h_1) \quad (20)$$

The mass balance:

$$m_r + m_s = m_w \quad (21)$$

$$m_{10} + m_6 = m_1 \quad (22)$$

- The solution pump.

$$W_{pump} = \frac{m_w}{\rho_{H_2O-BrLi}} (P_2 - P_1) \quad (23)$$

- The Heat exchange.

$$Q_{HX} = \varepsilon_{HX} \cdot C_{min} \cdot (T_4 - T_2)_{in} \quad (24)$$

$$T_3 = T_2 + \frac{Q_{HX}}{C_C} \ [°C] \quad (25)$$

$$T_5 = T_4 - \frac{Q_{HX}}{C_h} \ [°C] \quad (26)$$

$$C_C = m_{\,ws} \cdot C_{pc} \quad (27)$$

$$C_h = m_{ss} \cdot C_{ph} \quad (28)$$

- The solution valve

$$m_5 = m_6 \qquad \& \qquad h_6 = h_5 \quad (29)$$

- The generator.
  The energy balance.

$$Q_g = (m_7 \cdot h_7) + (m_4 \cdot h_4) - (m_3 \cdot h_3) \quad (30)$$

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- The condenser.

The energy balance.

$$Q_c = m_{7_{ref}}(h_7 - h_8) \tag{31}$$

The mass balance.

$$m_7 = m_8 \tag{32}$$

- The refrigeration valve

$$m_8 = m_9 \quad \& \quad h_8 = h_9 \tag{33}$$

- The evaporator.

$$Q_e = m_{9_{ref}}(h_{10} - h_9) \tag{34}$$

The coefficient of performance.

$$COP = \frac{Q_e}{Q_g + W_{pump}} \tag{35}$$

Table 1: The PEM electrolysis cell parameters.

Constant parameter	Symbol	Value
Faraday constant	F	96485 [C/mol]
Universal gas constant	R	8.314 [J/mol·K]
Area of electrolysis cell	A_{EC}	50.6 [cm^2]
Thickness of electrolysis cell	t_{EC}	0.0178 [cm]
The electrolysis temperature	T_{EC}	90 [ºC]
Pressures of component	$P_{H2,O2,H2O}$	101.325 [kPa]
The number of electron's	n	2
The membrane water activity	a	1
The electrons transfer coefficient	α	0.3
The maximum current density	i_L	2 [A/cm^2]

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Table 2: The PEM fuel cell parameters.

Constant parameter	Symbol	Value
Area of PEM fuel cell	A_{FC}	100 [cm^2]
Thickness of PEM fuel cell	t_{FC}	0.005[cm]
The fuel cell	T_{FC}	90 [ºC]
Pressures of component	$P_{H2,O2,H2O}$	101.325 [kPa]
Constant part of cell's resistance	R_c	0.0003 [Ω]
The parameter of fuel cell type	B	0.016
The parametric coefficients	F_1	- 0.948
	F_2	0.00286+0.0002ln(A)+4.3810-5 ·ln(CH2)
The parametric coefficients	F_3	7.6·10-5
	F_4	1.93·10-4
The membrane hydration level	ω	23
The maximum current density	i_L	1.5 [A/cm2]

Table 3: The (LiBr–H_2O) absorption refrigeration system parameters.

Constant parameter	Symbol	Value
The absorber temperature	T_{abs}	30 [ºC]
The generator temperature	T_{gen}	90 [ºC]
The condenser temperature	T_{con}	45 [ºC]
The evaporator temperature	T_{eva}	7 [ºC]
High region pressure	P_H	0.7 [kPa]
Low region pressure	P_L	9 [kPa]
mass of weak solution	m_w	0.05 [kg/s]
Heat exchanger effectiveness	η_{HE}	0.65

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The Result:

All the mathematical laws for each unit in the system were entered, including the variables and parameters, and all the operating assumptions were defined in the computer simulation program to understand the behaviour of the system as a whole and the degree of homogeneity of each unit with the other, the system was run on several variables and more than one operating state to understand the operating limits, the optimal operating state, and efficiency without causing any damage to each unit. The following table shows the results of the different operating of the system and notes the differences in voltage, electrical power, and coefficient of performance (COP).

Table 4. The effect of different operating conditions on the voltage of the cells, electrical power, and coefficient of performance (COP).

No	Changing Tin [ºC]	Electrolysis cell		Fuel cell		The cooling system
		Voltage [V]	Power [W]	Voltage [V]	Power [W]	COP
Stage.1	85	1.856	1.114	0.45	0.6357	0.6771
Stage.2	90	1.834	1.101	0.46	0.6464	0.7185
Stage.3	95	1.812	1.087	0.47	0.6565	0.7344

1. The PEM electrolysis cell

The performance of the first system "the hydrogen production unit", is first discussion. As shown in Curve (1) of Figure (2), the experimental results explain the effect of operating temperature on the cell voltage and power consumption. An inverse correlation is observed between these parameters; as the operating temperature increases, both the voltage difference and the electrical power required for operation decrease. The voltage decreases due to the change in the enthalpy and entropy of the Gibbs energy of the electrochemical reaction; consequently, the ideal or standard voltage of the cell decreases. Also, increased temperature improves the electrolyte's conductivity, which facilitates ion transport, thus reducing ohmic resistance. For the electrode voltage decrease is due

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to the reaction rates at the electrodes (anode and cathode) improve with temperature.

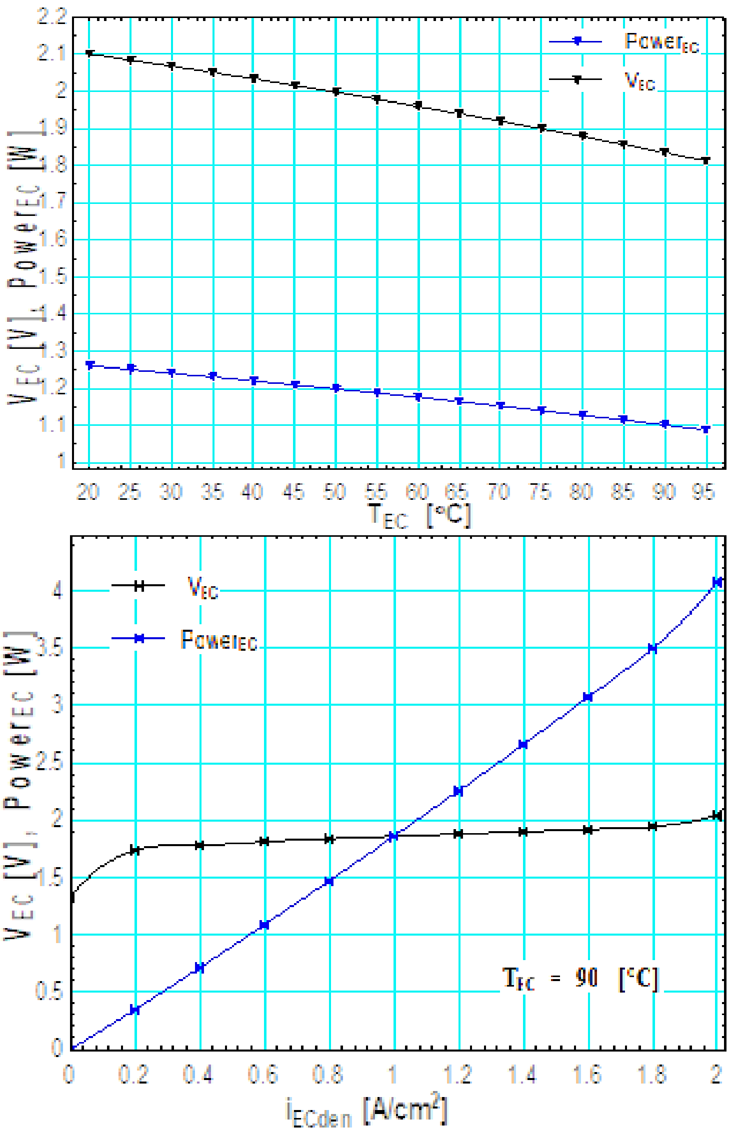

Figure 2. Effect of current density and operating temperature on PEM electrolysis cell voltage and power.

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This includes activation and concentration voltages, as a result of the properties of the materials used in manufacturing the electrodes being affected by heat, which affects the electrochemical reaction. The electrical power decreases with increasing temperature because the voltage required for the electrolysis process decreases, which means that the electrical energy required per unit of electrical current decreases because electrical power is related to current and voltage difference. Also, as a result of increasing temperature, thermoelectric efficiency increases because part of the required energy comes from the heat and not electricity, thus reducing the electrical load.

This point is considered positive in the operating mechanism of this system because we do not need high electrical power to break the covalent bond of the water molecule that separates its components and produces hydrogen gas due to the high operating temperature.

In curve (2), it is shown that the voltage difference and power increase with increasing current density. This behaviour reflects the presence of internal resistance within the cell. The voltage required to start the electrochemical reaction increases with current due to ohmic and electrochemical voltage. The flattening of the voltage curve at high current levels indicates that the cell has reached a stable state of operation process in terms of performance, also noted that the relationship between electrical power and current density is linear, meaning that it increases as the current density increases, even if the voltage curve begins to flatten. This means that power continues to increase as long as the current increases. This behaviour is useful for determining the optimal operating point of the cell, where high capacity can be achieved without exceeding the cell's voltage limits, which may lead to the degradation of the manufacturing materials or a decrease in efficiency.

2. The PEM fuel cell

The first curve in Figure (3) shows the relationship between operating temperatures, voltage difference and electrical power, where the voltage difference increases by a constant value and gradually with increasing operating temperatures.

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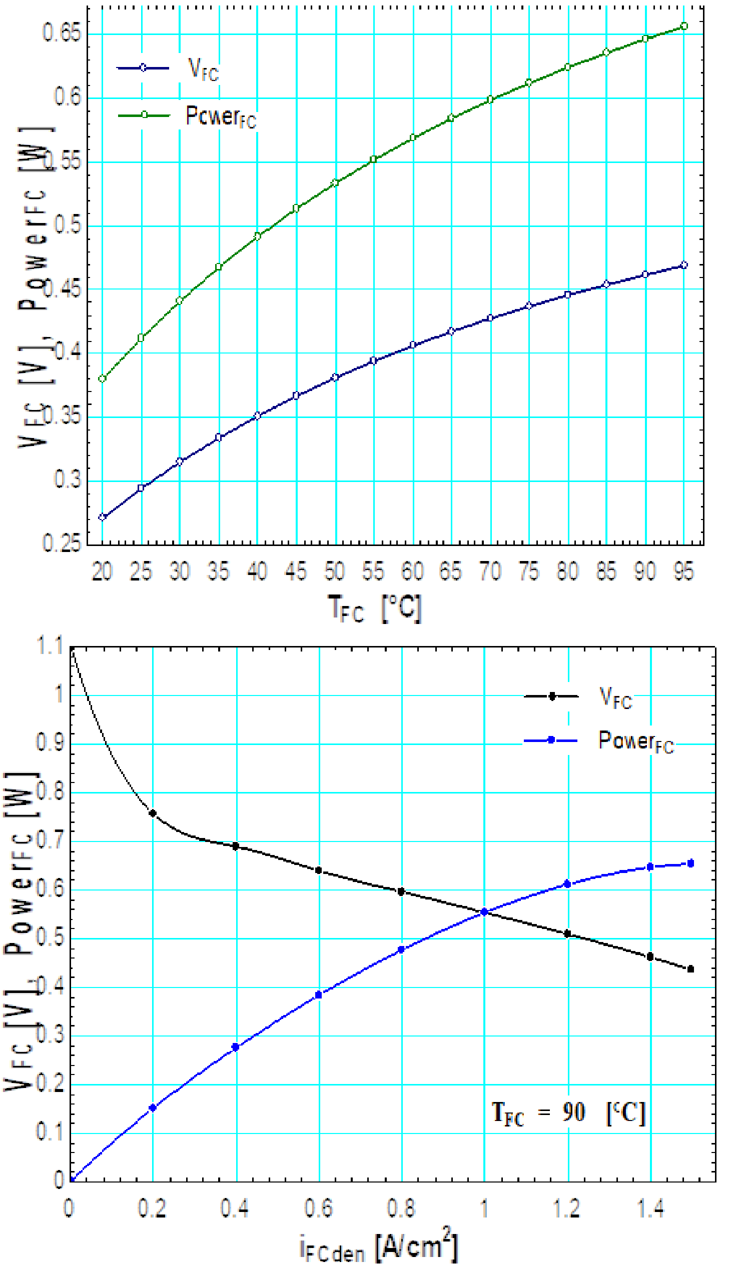

Figure 3. Effect the operating temperature and current density on the voltage and power of the PEM fuel cell.

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The voltage produced by the cell is not ideal, but is affected by several losses that reduce its actual value, including the activation voltage resulting from activation losses.

When the temperature rises, the molecules gain more kinetic energy, making it easier for them to overcome the activation energy barrier. This makes the chemical reactions inside the cell occur more easily and at a higher speed, thus reducing voltage loss and increasing the actual voltage of the cell. This effect is most prominent at the start of cell operation and at low currents. The ohmic voltage is occurring from the internal ohmic resistance of the cell components. The component most affected by temperature is the electrolyte membrane, which is a transports proton from the anode to the cathode. As operating temperatures increase, humidity and polymer chain movement within the membrane also increase, which in turn increases proton conductance. This increased conductance reduces resistance, thus decreasing voltage losses and raise in the final voltage at the cell ends.

As can be seen in the power curve, electrical power increases with increasing temperature, but at an increasing rate. The curve is not perfectly linear, but curves upwards, meaning that each increase in temperature results in a greater increase in electrical power. This is because electrical power is the product of voltage and current. Therefore, when the voltage increases, the power also increases, assuming the current remains constant or increases. More importantly, improved conditions inside the cell (faster reactions, lower resistance) not only increase the voltage but also allow the cell to generate a higher electrical current at the same voltage level. Heat also improves mass transport, i.e., the ability of the reactants (hydrogen and oxygen) to reach the catalyst. This prevents the cell from becoming overwhelmed when high power is required and allows it to provide a greater current.

In curve (2) in Figure (3), it shows the effect of cell voltage and electrical power by the change in current density at the operating temperature (90 ºC) this temperature is considered perfect state for operation in terms of voltage and electrical power produced, Since the voltage curve is most important for understanding the accuracy of cell behaviour and performance, a drop in voltage with increasing

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current is not a defect but rather a normal behaviour resulting from three different losses as showing in the curve. The activation loss occurs due to the low currents at the beginning of the curve, this loss results from the slow electrochemical reactions on the catalyst surface because these reactions require activation energy to start, this means that part of the cell's energy is consumed internally to overcome this energy barrier which is causing a significant initial drop in cell voltage.

In the middle region of the voltage curve, ohmic loss occurs, causing the voltage to drop almost linearly and steadily. This is considered the normal operating region. This loss results from the internal resistance of the cell components (electrodes, membrane, etc.) to the flow of ions and electrons. That is, the amount of voltage lost increases with the increase in current drawn, due to this resistance. There is also a third type of loss resulting from mass transport, which occurs at high currents, where there is a sharp, rapid drop in voltage, it appears as if the cell is about to suffocate. When a very high current is drawn, the cell consumes the reacting gases at a rate faster than it can deliver them to the reaction sites. Additionally, the water produced by the reaction accumulates rapidly and clogs the electrode pores, preventing gas flow. This critical shortage in the reactions causes a voltage collapse.

The curve of electrical power production, it increases with increasing current density until it reaches peak at a certain current density, after that it is begins to decrease because during peak period the cell reaches its optimal operating point where it gives the maximum possible power, and the balance between voltage and electrical current is at its best, but after the peak period, the cell enters a mass transfer loss phase where the drop in voltage becomes so sharp that it overwhelms any increase in electric current, and operation in this cell is considered non useful and harmful to its components.

3. The absorption cooling system unit

Figure (4) illustrates the results of an absorption cooling system that gets heat from the exhaust of a hydrogen fuel cell, it was operated at a temperature of (90ºC) and the performance coefficient of the cooling system was very satisfactory, reaching (0.71), and the

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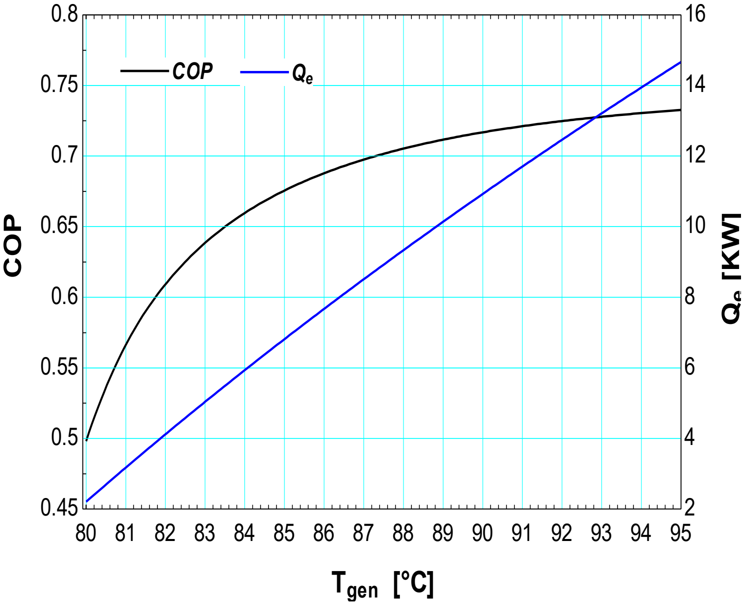
cooling temperature obtained was (7ºC). The generator temperature directly affects on the cooling system performance (COP) and cooling capacity (Q_e), when the generator temperature increase, the amount of heat energy available to evaporate the refrigerant fluid increases, this improving the system's ability to produce cooling relative to the energy input from the fuel cell. This leads to an increase in the cooling system's coefficient of performance (COP). Also, in the cooling power curve, (Q_e) increases with the increase in the temperature of the heat generator (T_{gen}) because the increase in temperature increases the kinetic energy of the molecules inside the solution and decreases the bonding force between the absorber fluid (LiBr) and the refrigerant fluid (H_2O). As a result of this process, the rate of separation of the refrigerant from the solution increases and it leaves as vapour. An increase in the amount of cooled steam generated in the heat generator increases the amount of refrigerant fluid which is reach in the condenser and then the evaporator, and thus the cooling capacity (Q_e) increases.



Effect of heat generator temperature on the cooling systems Figure 4. coefficient of performance.

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Conclusion

The experimental results indicate that increasing the operating temperature enhances the electrochemical performance of the hydrogen production unit, as a clear reduction in both cell voltage and power consumption was observed with rising temperature. This improvement can be attributed to several interconnected factors: firstly, the changes in enthalpy and entropy of Gibbs free energy, which reduce the standard cell voltage; secondly, the improved conductivity of the electrolyte, which facilitates ion transport and lowers ohmic resistance; and thirdly, the acceleration of reaction rates at the electrodes with higher temperatures. Therefore, it can be concluded that operating the system at elevated temperatures improves energy efficiency and reduces the electrical consumption required for hydrogen production. The optimal operating point is at the current density that achieves maximum power output, where the voltage and current balance is at its best. After this point, the accumulation of mass transport losses leads to a sharp decrease in performance; operation becomes unfeasible, and damages cell components. Operating the cooling system at higher generator temperatures significantly increases its efficiency, raising both the coefficient of performance and cooling capacity, making the exploitation of hydrogen fuel cell exhaust heat an effective means of producing additional cooling. This study demonstrates the feasibility of integrating PEM electrolysis, fuel cells, and absorption refrigeration into a single system. The results confirm that operating at higher temperatures improves electrochemical performance and enhances cooling efficiency. The proposed system effectively utilizes waste heat, leading to improved overall energy efficiency. This integration provides a promising solution for sustainable energy and cooling applications.

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