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Analytical Study for Using the Exhaust of Hydrogen Fuel Cell to Operate the Absorption Refrigeration System by Bromide Lithium Solution

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Abstract
The current work utilizes the waste heat of the cell exhaust in cooling systems to improve the hydrogen fuel cell efficiency. The analytical study is carried out using Engineering Equations Solver (EES) software. Simulation code, based on the laws of thermodynamics, is developed to assess performance of the Proton Exchange Membrane fuel cell (PEM) and the absorption refrigeration system. The results show that the hydrogen fuel cell is affected by the operating temperature. The voltage difference and the power of the cell increases with the increase in the operating temperature. The elevated generator temperature that is gained from the exhaust of the fuel cell enhances the performance factor of the absorption refrigeration system and the amount of cooling.
Keywords: *The PEM fuel cell, The absorption refrigeration system, Bromide lithium (LiBr-H_2O), The Hybrid Cooling System.*

الملخص
في هذا البحث تم استخدام حرارة العادم المهدورة لخلية الوقود الهيدروجينية في أنظمة التبريد، وذلك لتحسين كفاءة خلايا وقود الهيدروجين. تم إجراء الدراسة التحليلية باستخدام برنامج المحاكاة بإستخدام الحاسب الآلي (EES) (Engineering Equations Solver). وقد تم تطوير كود المحاكاة بناءً على قوانين الديناميكا الحرارية، لتقييم أداء خلية الوقود نوع غشاء التبادل البروتوني (PEM) ونظام التبريد بالامتصاص. أظهرت النتائج أن خلية الوقود الهيدروجين تتأثر بدرجة حرارة التشغيل. يزداد فرق الجهد وقدرة الخلية مع زيادة درجة حرارة التشغيل. تعمل درجة حرارة المولد المرتفعة التي يتم الحصول عليها من عادم خلية الوقود على تحسين عامل أداء نظام التبريد بالامتصاص وكمية التبريد.
الكلمات المتاحة: *خلية الوقود (PEM)، نظام التبريد الإمتصاصي، بروميد الليثيوم (LiBr–H_2O)، نظام التبريد الهجين.*

1. Introduction

The renewable energy has increasingly become a major part of scientific research not only because it is clean but also due to supply instability throughout the world [1]. Among other clean energy sources, fuel cells are a simple and easy-to-use technology for power generation. They are electrochemical devices that convert hydrogen fuel into electrical energy through several chemical reactions that take place in the cell body. These devices do not produce a huge percentage of harmful pollutants because the most important products of this cell are electricity power, pure water and heat [2].

Several clean renewable energy sources are used in refrigeration systems in previous research, including solar energy. A study conducts in India examined the use of the absorption refrigeration system powered by solar energy through simulating a single effect LiBr-H2O absorption refrigeration system combined with solar panels to supply the thermal generator of refrigeration system with the necessary heat. Because of inconsistency for radiation throughout the day, the system worked efficiently only for few hours [3].

Another research designed an absorption refrigeration system that works with solar diffusion to reduce costs, especially in areas that do not have electricity network. The system consists of a thermally driven bubble pump which is used to circulate the refrigerant and absorbent fluid components of the system and heat pipe solar collectors as the heat source, the system operated at different pressures. Again, limited availability of solar energy throughout the day was the major downside of the system [4]. Therefore, it is necessary to search for another source of renewable sources. Hydrogen fuel cells can be one of the best energy source alternatives that can be produced and stored, in the form of hydrogen gas, in cylinders and use it at any time of the day.

The fuel cell technology can be more efficient by improving the fuel cell operation. This work applies the fuel cell in the refrigeration fields as the best alternative to the solar.

The refrigeration systems are divided into two main sections: compression cooling systems and absorption cooling systems. The compression refrigeration system depends primarily on a compressor to increase the pressure of the refrigerant fluid, while in the absorption refrigeration system relies on a heat unit to increase the temperature of the refrigerant fluid. Accordingly, the proton exchange membrane (PEM) fuel cell that generates a temperature about 100°C can be employed to run the absorption refrigeration systems. The current study is to examine and quantify the efficiency of such hybrid cooling system through a simulation model.

Fuel cells are defined as an electrochemical device that converts the chemical energy in the fuel into electrical energy by several chemical reactions. As a result of these chemical reactions, the heat, pure water and most importantly electrical energy are produced. Furthermore, this operation is stable with steady performance because it depends mainly on the formation and dissolution of the elements represented in the chemical equations of the cell. It does not produce noise or vibration [5].

Generally, the fuel cells are classified according to operational parameters, design conditions or required application characteristics. The operating conditions is the common one because the operating temperature is the prominent influencing factor in hybrid systems performance. There are high operating temperature fuel cells ranges from such as the solid oxide fuel cell (750-1000 ℃) and the carbon molten fuel cell (650 ℃). In addition, there are low operating temperature fuel cells including the proton exchange membrane (PEM) fuel cell (80-100 ℃) and phosphoric acid fuel cell (160-250 ℃) [6].

The PEM fuel cell is fixable chosen in this study due to several reasons. The PEM fuel cell does not require complex supporting devices to start a continuous operation. Moreover, the operating temperature of the cell is as low as 100°C and the operating pressure is low, which provides operational safety and saves operational cost. Additionally, with a simple mechanical design, the PEM fuel cell produces a high voltage with steady current density and high electrical capacity [7].

The absorption refrigeration systems can be defined as a cooling technology with a thermal region, which uses a heat source to deliver the energy, needed to run a cooling process. The absorption refrigeration system consists four main units: absorber, heat generator, condenser and evaporator. The compressor unit that is commonly used in conventional cooling systems

has been replaced by an absorbent unit and a heat generator. Further, a pump and expansion valves are used to increase and decrease the refrigeration fluid pressure [8].
The principle operation of the fuel cell is working by set of chemical reactions; some of these reactions are dissociation and decomposition. The fuel cell starts work when pumping the hydrogen gas from storage cylinders in the anode side of the cell as shown in figure (1). The hydrogen gas atoms pass through the gas passages where gas atoms spread out on the surface of a separator (Catalyst), the catalyst is made from carbon fibres to separate hydrogen atoms into protons and electrons.

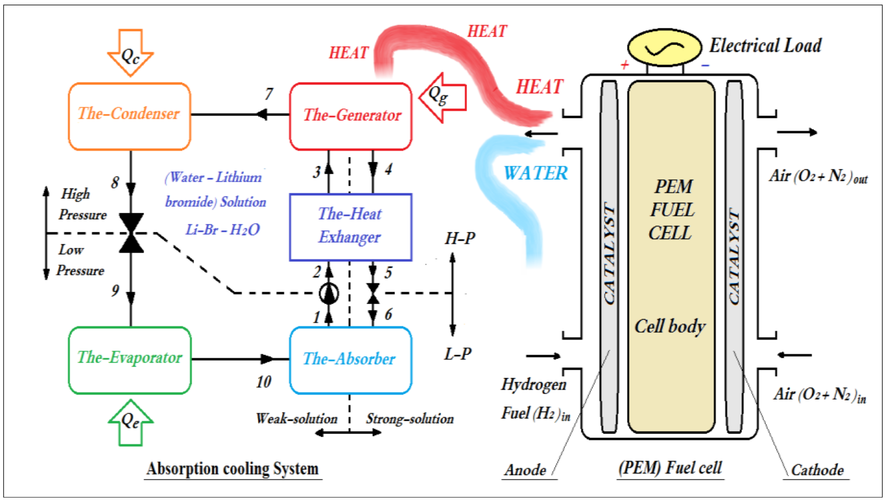

Figure.1. The process of integrating the fuel cell and absorption cooling system

The proton exchange membrane make the protons to cross and does not allow the electrons, then the electrons move to the electrical conductor which is connected with electrical load, after that the oxygen gas is pumping in the cathode side to combined with the electrons which is come from electrical load and protons to forming the pure water [9].
The absorption refrigeration system works with three fluids in the cycle: Strong concentration solution, weak concentration solution, water vapor (cooling fluid), as shown in Figure (1). The weak concentration solution leaves the absorber unit to pump at stage (1) to increase the pressure, after that enters to the heat exchange unit in stage (2) to raising the temperature by heat exchange process with strong concentration solution, and then enters to generator unit at stage (3). In the generator unit due to the gained temperature from the exhaust gases of fuel cell, the water vapor separates from the lithium bromide salt, And the solution become strong concentration which is leave to heat exchange unit in stage (4). Finally, enter to the absorber unit. About the water vapor, leave the generator to the condenser unit in stage (7) to decrease temperature then to expansion valve at stage (8) to reduce pressure. After that enters to the evaporator unit to cooling the require area. Moreover, this process repeats and repeat in cycle [10].

2. Research Methodology

2.1. The Mathematical Model of Whole System

The mathematical model is one of the most important design steps to establish any system because it captures the system's operational, stability state and behavior of the system. In

addition, the optimal properties and operating conditions can be identified for the system through this model. Several thermodynamics equations and laws construct the method.
The Engineering Equation Solver (EES) simulation computer programing is used. A number of assumptions are considered in the simulation code, including:

1. The system state is consider a steady state steady flow.
2. The heat losses in all thermal units are consider negligible.
3. There is no pressure loss, especially in the pipes.
4. The work of pump is neglected because is a small value.
5. The enthalpy state in the expansion valves of the solution and refrigerant fluid does not change.

The following is description of chemical reactions that generate heat, water and electricity [11]. A lay out of equations employed in the analytical model are also present [5, 12, 14].

2.2. The PEM fuel cell model.

1. The chemical reactions of Fuel Cell are presented below along with parameters used in the study code, which are summarized in Table.1.
   - The general electrochemical reaction of PEM fuel cell

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

   - The anode side

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

   - The Cathode side

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (3)$$

2. The voltage of PEM fuel cell
   - The General voltage of cell

$$V_{cell} = E - V_{act} - V_{ohm} - V_{conc} \quad (4)$$

   - The reversible voltage

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

(5) The Activation voltage of cell

$$V_{act} = -\xi_1 + \zeta_2 \cdot T + \xi_3 \cdot T \cdot \ln(C_{O_2}) + \zeta_4 \cdot T \cdot \ln(\mathrm{i_{FC}}) \quad (6)$$

   - The ohm voltage of cell

$$V_{ohm} = i_{FC}(R_m + R_c) \quad (7)$$

$$R_m = \frac{\rho_m \cdot l}{A} \quad (8)$$

$$\rho_m = \frac{(181.6 \cdot [1 + 0.03 \cdot \left(\frac{i_{FC}}{A}\right) + 0.062 \cdot (\frac{T}{303})^2 \cdot (\frac{i_{FC}}{A})^{2.5}])}{(\left[\Psi - 0.364 - 3 \cdot (\frac{i_{FC}}{A})\right] * exp^{\left(\frac{4.18 \cdot (T-303)}{T}\right)})} \quad (9)$$

Where Ψ 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

$$V_{conc} = -B \cdot \ln(1 - \frac{i}{i_L}) \quad (10)$$

   - The power of cell

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

Table 1: Setting Parameters of the fuel cell

Constant parameter	Symbol	Value
The fuel cell temperature	T	343 K
The partial pressure of gases	P_{H_2}	1 atm
	P_{O_2}	1 atm
	P_{H_2O}	1 atm
Area of cell	A	50.6 cm^2
The cell membrane thickness	L	178 μm
Faraday's constant	F	96485 $C/mole$
Number of electrons	z	2
Gas constant	R	8.314 $J/mole{\cdot}K$
The constant part of cell's resistance	Rc	0.0003 Ω
The parameter of fuel cell type	B	0.016
The sum of parametric coefficients of Activation voltage	ξ_1	-0.948
	ξ_2	$2.86 \cdot 10^{-3} + 2 \cdot 10^{-4}\ln(A) + 4.381 \cdot 10^{-5}\ln(C_{H_2})$
	ξ_3	$7.6 \cdot 10^{-5}$
	ξ_4	$-1.93 \cdot 10^{-4}$
The input current	i_{FC}	70.84 A
The limiting current density	i_L	1.5 A/cm^2

2.3. The H2O-Brli Absorption Refrigeration System Model

The first law of thermodynamic is applied to each of the following units.

1. The absorber.
   - The Energy balances

$$Q_a = (m_{10} \cdot h_{10}) + (m_6 \cdot h_6) - (m_1 \cdot h_1) \quad (12)$$

The mass balances

$$m_r + m_s = m_w \quad (13)$$

$$m_{10} + m_6 = m_1 \quad (14)$$

The solution pump

$$W_{pump} = \frac{m_w}{\rho_{H_2O-BrLi}}(P_2 - P_1) \quad (15)$$

The Heat exchange

$$Q_{HX} = \varepsilon_{HX} \cdot C_{min} \cdot (T_4 - T_2)_{in} \quad (16)$$

$$T_3 = T_2 + \frac{Q_{HX}}{C_C} \quad (17)$$

$$T_5 = T_4 - \frac{Q_{HX}}{C_h} \; [°C] \quad (18)$$

$$C_C = m_{ws} \cdot C_{pc} \quad \& \quad C_h = m_{ss} \cdot C_{ph} \quad (19)$$

2. The solution valve

$$m_5 = m_6 \quad \& \quad h_6 = h_5 \quad (20)$$

3. The generator
   - The energy balance

$$Q_g = (m_7 \cdot h_7) + (m_4 \cdot h_4) - (m_3 \cdot h_3) \quad (21)$$

4. The condenser

- The energy balance

$$Q_c = m_{7_{ref}}(h_7 - h_8) \quad (22)$$

- The mass balance

$$m_7 = m_8 \quad (23)$$

The refrigeration valve

$$m_8 = m_9 \quad \& \quad h_9 = h_8 \quad (24)$$

5. The evaporator

- The energy balance

$$Q_e = m_{9_{ref}}(h_{10} - h_9) \quad (25)$$

$$COP = \frac{Q_e}{Q_g + W_{pump}} \quad (26)$$

The work of pump can be ignored because is smallest value.

3. Result And Discussion

3.1. The Model Validation

The parameters of fuel cell (PEM) was input in simulation code are shown in Table .1. The absorption refrigeration system was operate at variable temperatures, the absorber 30°C, the heat generator 88°C, and the condenser 45°C, and the evaporator 10°C, the high and low pressure is (0.7, 9 kPa), the flow rate (0.05 kg/s) and the efficiency of the heat exchanger (0.65), the coefficient of performance was (0.7069).

In order to ensure the validity of the results were compare, and running the present model with the parameters in the research papers [8-9] were show in follow table.2.

Table 2: Show validation between present study and anther research paper [8, 9]

#	Study	Data input	COP in research paper	COP of present study
1	Q.Al-Amir (2017) [12]	Same data in Q.Al-Amir (2017)	0.779	0.7785
2	J.Wonchala (2014) [13]	Same data in J.Wonchala (2014)	0.71	0.711
3	S.Mohamed [3]	Same data in J.Wonchala (2014)	0.857	0.8567

As can be seen in the third point in Table.2. This simulation code was running with the same parameters as the research paper [3], and obtained results identical to this paper, which was powered by solar flat plate collector.

3.2. The Performance Of PEM Fuel Cell

The fuel cell voltage is clearly affected by operating temperature. Therefore, the cell voltage increases with increasing in the operating temperature because the voltage consists of several voltage differences; the reversible, activation and ohm voltages of the cell as shown in Figure.2.

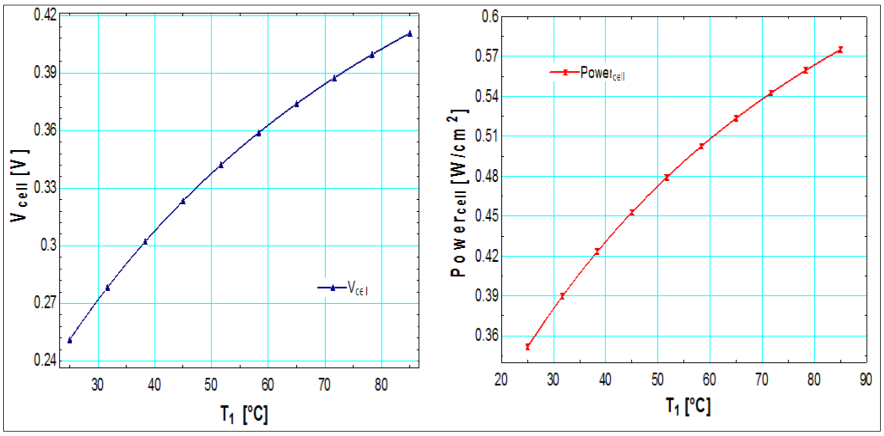

Figure.2. Effect the operation temperature on voltage and power of PEM fuel cell

The reversible voltage of the cell is considered as a function in the operating temperature, with partial pressures of the gases, the activation voltage is considered as a function in temperature only, the activation voltage depends on the activation energy for start reaction, and temperature is one of the most important factors for the start the reaction and occurrence. The occurrence of a chemical reaction at the electrodes is affected by increase in temperature. Also, the concentration of gases in the activation voltage is affected by the temperature when gas molecules is diffuse on the surfaces of electrodes and catalysts. The ohm voltage is affected by temperature due to the specific member resistance because the thermal properties of the membrane material are affected by temperature. The power of cell is directly affected by the operating temperature due to the increase in the cell voltage, thus the value of the power increase to overcome these voltages and resistances.

3.3. The Performance Of Absorption Refrigeration Systems

In the refrigeration system the temperature of the heat generator derived from the fuel cell exhaust has a clear effect on the results of the cooling system, as shown in Figure 3. The performance coefficient of refrigeration system is increase by increasing the temperature of the heat generator and the amount of cooling. As for the concentration ratios of the solution, the low concentration solution is not affected by the temperature of the heat generator and there is no change in its value, because the low concentration solution is not exposed to the heat of the heat generator before entering into the generator after leaving the pump and heat exchanger.

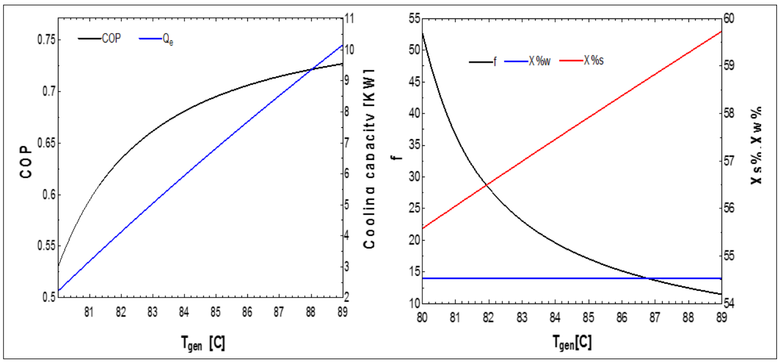

Figure.3. Effect T_{gen} on COP, cooling capacity, circulation ratio and LIBR concentration

The strong concentration solution it is affected very clearly by the temperature of the heat generator, when the temperature of the heat generator increases the concentration of the solution due lithium bromide salt crystals increases inside the heat generator, because the amount of heat works to boil the solution. As for the circulation ratio which is the ratio between the low and high concentration solution, it is negatively affected by the temperature of the generator, that is, the circulation ratio of the solution decreases with increasing temperature of the generator due to the affected the strong concentration solution by the temperature of the generator, the boiling process and the influence of the bromide salt.
The change in the temperature of the thermal generator plays an important role in the process of heat transfer in thermal units, as shown in Figure 4. When the temperature of the thermal generator increases, the four main units of the system are affected positively, this means that the rates of heat transfer increase with the increase in the temperature of the generator, because the only heat source for the system is the temperature of the thermal generator, and the thermal path in the system is linked to each other, when any changes were occurring all units are affected by temperature.

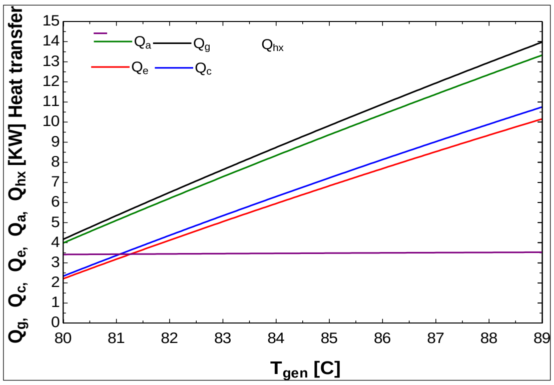

Figure.4. Effect T_{gen} on Heat transfer of absorption refrigeration system units

4. Conclusion

Few studies have discussed the promising benefits of integrating the fuel cell with the absorption refrigeration system. This study utilizes a numerical code to capture the efficiency of such hybrid system by taking advantage of the heat produced by the fuel cell to enhance its performance. A clear effect on the cooling system operation performance is observed. The efficiency was improved when the cooling system was operated by hydrogen fuel, as the results of the present cooling system were compared with a cooling system that was powered by solar flat plate collector and, the results were very close about (0.857). However, solar energy has disadvantage, as the temperature of solar energy is not continuous due to the weather conditions or the state of solar radiation upon reaching the evening period. Thus, the performance coefficient of the solar cooling system will decrease. But the fuel cell technology cooling system is stable since hydrogen fuel is available all the time in the gas storage cylinders.

5. Recommendation

1. Preparing analytical study by adding a system that produces and provides hydrogen gas for the fuel cell.
2. Create a dynamic model, that studies the operating status of the system as a whole as a function of time.
3. Create another analytical study with other fluid of the absorption refrigeration system such as Ammonia Water (NH3-H2O).
4.

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7. Abbreviations

Abbreviation	Definition	Unit
PEM	Proton Exchange Membrane	-
LiBr-H_2O	lithium bromide-water	-
EES	Engineering Equation Solver software	-
H_2	The Hydrogen gas	-
O_2	The Oxygen gas	-
H_2O	The water	-
H^+	The proton of hydrogen gas	-
e^-	The electric charge	coulomb
P_{H_2}	The partial pressure of hydrogen gas	atm
P_{O_2}	The partial pressure of oxygen gas	atm
P_{H_2O}	The partial pressure of water	atm
V_{cell}	The general voltage of fuel cell	Volt
E	The reversible voltage of fuel cell	Volt
V_{act}	The Activation voltage of fuel cell	Volt
V_{ohm}	The ohm voltage of fuel cell	Volt
V_{conc}	The concentration voltage of fuel cell	Volt
ρ_m	specific membrane resistance	Ω.cm
$Power_{fuel\ Cell}$	The power of fuel cell	Watt
Q_a	Heat duty of absorber	KW
Q_g	Heat transfer rate of generator	KW
Q_c	Heat transfer rate of condenser	KW
Q_e	Heat transfer rate of evaporator	KW
Q_{HX}	Heat transfer rate of heat exchanger	KW
m_i	Mass flow rate of (i) component	Kg/s
$m_{7_{ref}}$	Mass flow rate of refrigerant	Kg/s
h_i	Enthalpy at (i) stream of cycle	KJ/Kg
W_{pump}	Pump work	Watt
$\rho_{H_2O-BrLi}$	Denisty of lithium bromide-water	Kg/m^3
T_i	The temperature at (i) stream	℃
T_{gen}	The temperature of generator	℃
P_i	The pressure at (i) stream	bar
ε_{HX}	The effective of Heat exchanger	-
C_i	Heat capacity of fluid at (i)	[W/K]
COP	The coefficient of performance	-