# A novel cogeneration system consisting of a proton exchange membrane fuel cell coupled to a heat transformer for eletricity, heat and distillation purposes

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## Abstract

This study focuses on the potential of a novel cogeneration system consisting of a proton exchange membrane (PEM) fuel cell and an absorption heat transformer (AHT). The dissipation heat resulting from the operation of the PEM fuel cell is used to feed the heat transformer, which is integrated to a water purification system. Therefore, the products of this cogeneration system are heat, electricity and distilled water. The heat delivered during water condensation is recycled to the generator and evaporator of the heat transformer increasing its efficiency. The simulation for the PEM fuel cell is presented. In addition, the results of the fuel cell system modeling are used to obtain experimental data from the operation of the AHT. This is possible due to the fitting in power and temperatures between the outlet conditions of the fuel cell and the inlet requirements of the AHT. The results of the simulation obtained through a thermodynamic model were used to perform experimental runs in order to estimate the performance parameters of the overall system. Experimental coefficients of performance are reported for the AHT as well as the overall cogeneration efficiency for the integrated system. The results show that experimental values of coefficient of performance of the heat transformer and the overall cogeneration efficiency, can reach up to 0.256 and 0.662, respectively. This represents an increment in 21% of efficiency, compared to the fuel cell efficiency working individually. This study shows that the combined use of AHT systems with a fuel cell is possible and it is a very feasible project to be developed in the Centro de Investigación en Energía (Centre of Energy Research), México.

## Keywords

Fuel Cells, Water-Lithium bromide, heat transformers, desalination, cogeneration, advanced cycles.

## 1. Introduction

In recent years, it is noteworthy the effort aimed to increase the energy efficiency and reduce damage to the environment. The use of renewable energy and waste heat are getting increasing interest as a means to achieve this goal. Cogeneration is among diverse types of technologies, in which the waste heat is used for power generation, producing electricity and heat simultaneously. It is also known as Combined Heat and Power, CHP.

Regarding to electricity generation, the use of fuel cells has become a current application for cogeneration systems. The fuel cell transforms the chemical energy into electricity, heat, and water. These devices have high efficiency, low emission and noise, and a modular design. The

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operating temperature ranges, and thus the level of rejected energy, depend on the type of fuel cell. The waste heat released by a proton exchange membrane fuel cell (PEMFC) enables one to obtain hot water with temperatures up to 80 °C, which is suitable for the operation of sorption refrigeration cycles [1, 2]. A well resumed description about operating principles of fuel cell and particularly PEMFC is found in [3].

The integration of fuel cells and heat pumps has been slightly explored. Very few works have been reported in this field, specifically for absorption systems. Pilatowsky et al. [3] performed a simulation in which a 1kW PEMFC was operated with a monomethylamine–water absorption system. The results show an increase of the total efficiency of the system and the feasibility of using a PEMFC for cooling. Darwish [4] suggested the use of a commercial phosphoric acid fuel cell PAFC to operate air conditioning systems (combined mechanical vapor compression and absorption water chillers) for big buildings in Kuwait. They do not perform a thermodynamic simulation of the cycle, but introduces the possibility of this combined system in order to use the fuel cell power output to supply the needed energy for the average as well as the peak A/C system capacity. Margalef and Samuelsen [5] worked with the integration of a molten carbonate fuel cell and a Water-LiBr absorption system, both commercially available, in order to assess the practical opportunity of serving an early distributed generation combined cooling, heating, and power (CCHP) market. They modelled both components individually and considered some strategies to reduce the inlet temperature of the chiller, obtaining good results for the coupling.

Regarding to applications of heat transformers, they have been used to increase the temperature of waste heat. In this sense, they can be coupled to a water purification system and obtain a type of desalination technology [6-8]. Huicochea et al. [9] presented the experimental results of the integration of a portable water purification system and an AHT. They obtained the temperatures working ranges for the system and good results for water quality. Romero and Rodriguez [10] developed a theoretical model to describe the operation of an AHT for water purification using low grade waste heat. They showed the rise in the COP obtained through the variation of different operating conditions. Later, Huicochea and Siqueiros [11] worked on the maximization of system efficiency by recycling part of the heat obtained in the absorber to one component of the heat source. The component can be the generator or the evaporator. This study carried out a comparison of the coefficients of performance obtained when the absorption heat is recycled to the only one component and two components. The results indicated that the higher increment was obtained when the heat is recycled in the generator. Farther experimental studies were carried out for this system. Rivera et al. [12] developed an energy and exergy experimental evaluation to determine the COP of the system, as well as the irreversibility of each component. For this study, the absorber, the generator and the economizer resulted to be the components which contribute with more irreversibility to the system, and they also probed that it is a good option to use recycled heat. The use of residual heat from a fuel cell for this kind of systems is a very attractive application.

As it is deduced from the above review, the results of the combined use of fuel cells and absorption systems have been obtained only by theoretical simulation, and the coupling with heat transformers has not been explored yet. Therefore, in this work a novel cogeneration system formed by a PEMFC and an AHT is analyzed. In order to accomplish this, a simulation of the PEMFC and experimental data of a heat transformer have been carried out. The efficiency of the cogeneration, as a measure of the overall system efficiency is defined and reported.

## 2. The fuel cell

As already mentioned in the previous section, fuel cells transform the chemical energy into electricity, heat, and water. The energy balance in a fuel cell can be carried out as follows:

$$\dot{Q}_T = P_e + P_t + \dot{Q}_{op} \qquad (1)$$

This expression means that the total energy produced by the fuel cell $\dot{Q}_T$ is distributed in electric power $P_e$, the available heat $P_t$ which represents the energy that can be recovered to be used in other process, and the heat necessary for the fuel cell operation $\dot{Q}_{op}$, which cannot be recovered.

Membranes fuel cells cannot operate at temperatures higher than 120ºC and therefore their functioning and efficiency are improved for temperatures lower than 100ºC, typically up to 80ºC. The highest efficiency is obtained at 60ºC due to membrane humidification [13]. The operating temperature also restricts the water production, as well as the operating pressure. An increase in temperature and a decrease in pressure reduce the hydrogenesis [14].

The fuel cell used for simulation purposes makes use of nafion membranes and is fed with hydrogen and oxygen. For this particular fuel cell, the simulated electrical power varies from 1106.1 W at a temperature of 23 ºC, a maximum value of 4363.3 W at 80 ºC and 3713.4 W at 100 ºC. The variation of $P_e$ occurs because of the relation of the current density and temperature: the current density is maximum at 80 ºC and then $P_e$ decreases with an increasing temperature.

## 3. Experimental facility. An absorption heat transformer for distillation purposes

In the following, a brief description of the experimental facility is presented.

Figure 1 presents a schematic diagram of an absorption heat transformer integrated to a water distillation system. Figure 2 shows a photograph of the experimental facility.

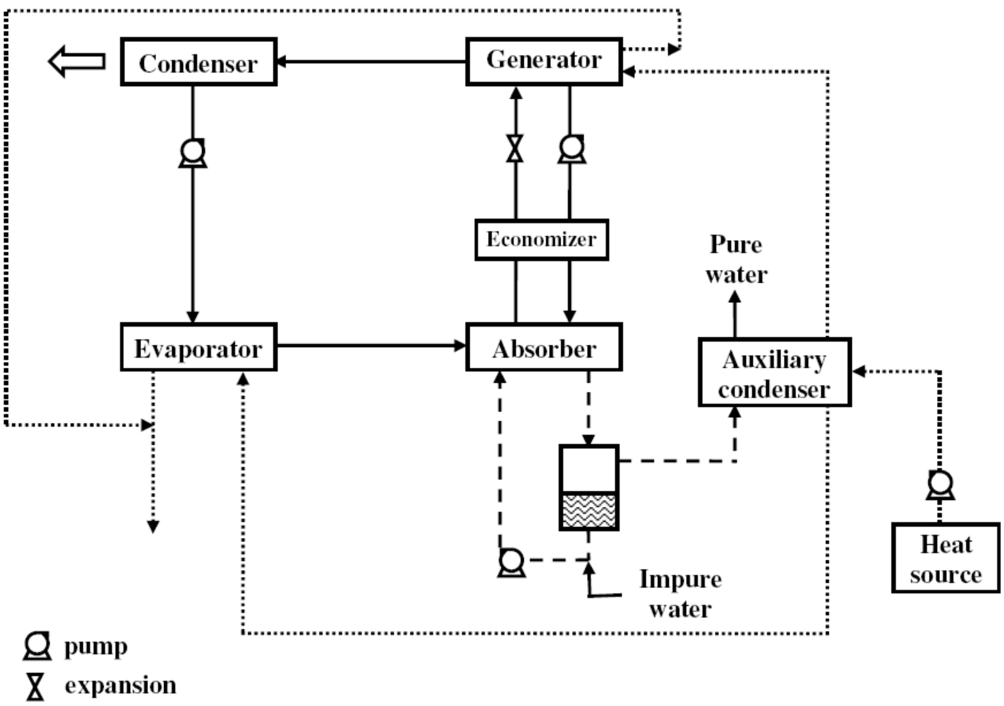


Figure 1. Schematic diagram of the absorption heat transformer for water distillation


Figure 2. Photograph of the experimental facility.

3.1. Experimental equipment description

The heat supplied to the generator and evaporator was obtained with a thermal bath and a variable electric resistance, used a commercial centrifuge pump of 0.5 horse power and 3450 revolutions per minute. The heat was extracted from the condenser with an external circuit, by using a commercial centrifuge pump of 1 horse power and 3450 revolutions per minute. The gained heat in the absorber was removed by the water purification system. Type J thermocouples and an Agilent data acquisition unit of 6½ digits with a Bench Link Data Logger software for temperatures measurement were used. All temperatures were calibrated to a temperature standard, with a maximum error of ± 0.3°C in the range from 0.0°C to 105.0°C. Two pressure transducers with design exactitude of ± 0.25% in the total range were used to measure low and high pressure. The relation between direct voltage and pressure was obtained using an analogical pressure standard with a full scale accuracy of ± 0.25% and with a resolution of 666.6 Pa. Solution flows were measured with two analogical flowmeters with a reading accuracy of ± 2%. Water - lithium bromide concentrations in the generator and absorber were measured using a refractometer with an accuracy of ± 0.0002 and a correlation of the refraction index obtained in a previous work. Two analogical flowmeters with a full scale accuracy of ± 3% were used to measure water flows of the generator and evaporator, impure water flow was measured with an analogical flowmeter with a full scale accuracy of ± 2%. An analogical flowmeter with a full scale accuracy of ± 3% was used to measure flows of condenser. A thermal insulator made of an expanded elastomer with a thermal conductivity of 0.040 W/m K was used.

3.2. The water purification system

Under specific conditions of atmospheric pressure and chemical composition, impure water reaches the boiling point and goes out in two phases (liquid and steam) to a phase separator. In its liquid phase, the impure water returns to the suction pump in order to be taken again to the absorber; steam goes to an auxiliary condenser where it transfers heat to the heat source. The difference in temperature between steam and the heat source allows an increase of the heat source temperature. The water level to purify in the phase separator is constant and cumulative salts are periodically drained.

## 3. Proton exchange membrane fuel cell (PEMFC) and absorption heat transformers

For the case under study, the available heat ($P_t$ in Eq. (1)), is used to activate the generator and evaporator of the heat transformer:

$$P_t = \dot{Q}_{GE} + \dot{Q}_{EV} \quad (2)$$

Figure 3 illustrates the schematic diagram of the cogeneration system under study, which shows the coupling of the PEMFC and the AHT, and their corresponding inputs and outputs.

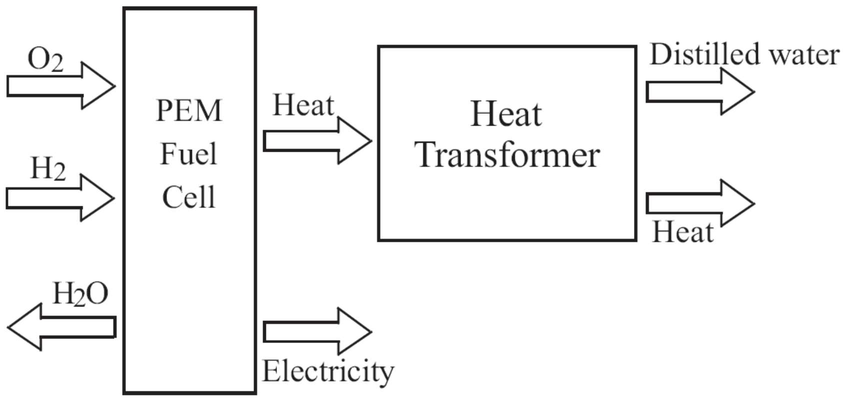


Figure 3. Schematic diagram of the cogeneration system formed by a proton exchange membrane fuel cell and an absorption absorption heat transformer

## 4. PEMFC modelling

The quantity of electric energy $P_e$ produced by a PEMFC has been already studied, concluding that it depends mainly on two parameters: the gas pressure and the operating temperature, according to the following expression [15]:

$$P_e = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}\left(T_{PEM} - T_0\right) + \frac{RT_{PEM}}{2F}\left(\ln\left(P_{H_2}\right) + \frac{1}{2}\ln\left(P_{O_2}\right)\right) \quad (3)$$

Where ΔG is the Gibbs free energy or standard free energy of formation available for work, $T_{PEM}$ is the absolute temperature of the reaction and ΔS is the entropy change for the reaction.

Considering Eq. (3) and assuming a reference temperature $T_0$=25ºC (standard laboratory conditions), the evaluation of $P_e$ at constant current is a function of the operating temperature T. The fuel cell efficiency remains almost constant if the ratio between the hydrogen and oxygen pressure is kept lower than 3. It is advisable, according to reported experimental studies [16], not to exceed this relation in order to maintain the correct operation of the fuel cell. The thermodynamic values (T, P) used for the simulation have been acquired from the literature available [17, 18]. The maximum total energy variation ($P_t + P_e$) produced by the PEMFC will be a function of the operating temperature $T_{PEM}$, having a linear behaviour [1].

The thermodynamic efficiency is estimated according to Eq. (4):

$$\eta = \frac{\Delta G}{\Delta H} = 1 - \frac{T\Delta S}{\Delta H} \quad (4)$$

Where ΔH is the standard enthalpy of formation. According to reported values, this efficiency can reach 83% at 25ºC [13].

It is important to mention that the data reported in [19] for the case of a 10kW PEMFC, presented a similar tendency compared to the results obtained for the simulation of the 5 kW PEMFC considered here.

## 5. Estimation of electric and thermal power

The thermodynamic efficiency η of a fuel cell is practically constant between 20ºC and 60ºC. Nevertheless, for higher values (80ºC - 120ºC) η diminishes [15]. On the other hand, the current density increases proportionally with temperature, resulting that the maximum electric energy that can be transmitted by electrodes occurs at 80ºC. The optimum values for $P_e$, resulting from the simulation of this particular cell, are in concordance with Nafion 112 and Nafion 117, proposed in the literature [15] which is based on the load density extrapolated to $P_e$=5 kW.

Figure 4 presents the electric and thermal energy, $P_t$ and $P_e$, resulting from Eqs. (3) and (4), against the fuel cell operating temperature. The relation between , $P_t$ and $P_e$ is 0.76 as mean value. This means that $P_e$ is 24% higher than $P_t$ produced by the fuel cell, which matches up with results reported in Kazim et al. [16].

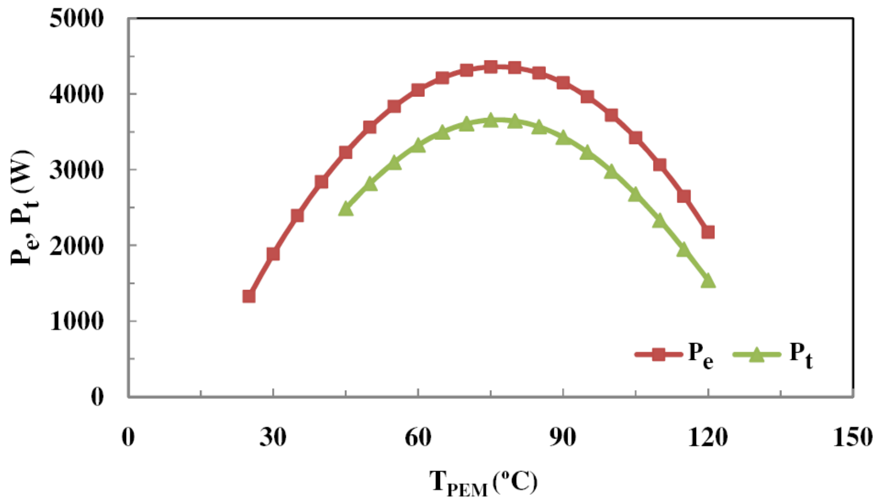


Figure 4. Thermodynamic efficiency, electric and thermal power as a function of temperature

## 6. Efficiency concepts

The efficiency concepts used for the description of the systems performance studied here, are defined next.

For an AHT, the coefficient of performance is given by Eq. (5):

$$COP = \frac{\dot{Q}_{AB}}{\left(\dot{Q}_{GE} + \dot{Q}_{EV} + W_{pump}\right)} \quad (5)$$

For the system presented, the cogeneration efficiency can be estimated as:

$$EOC = \frac{(P_e + \dot{Q}_{AB})}{(P_t + P_e)\eta} \quad (6)$$

The electric efficiency of the fuel cell is defined as:

$$Ee = \frac{P_e}{P_e + P_t} \quad (7)$$

## 7. Results

Taking into account the simulation results, the experimental runs were carried out using the experimental facility described in section 3. The objective of these tests is to determine the performance of the integrated system formed by the PEMFC and the heat transformer for distilled water production. A number of 17 experimental runs were carried out, however just 8 points were appropriate for the fuel cell conditions due to difficulties regarding stability conditions and control systems

In the following, the different variation of operating parameters and its influence over the cogeneration efficiency and distilled water produced is analyzed.

The results corresponding to distilled water mass flow rate and efficiency of cogeneration *EOC* against the absorber heat load $\dot{Q}_{AB}$ are plotted in Figure 5. It can be seen that both the quantity of distilled water and EOC increase with an increment of $\dot{Q}_{AB}$. This behavior was expected since if $\dot{Q}_{AB}$ increases, the heat used to produce purified water also increases. On the other hand, from Eq. (6) it is clear that the increment of $\dot{Q}_{AB}$ leads to higher *EOC*. In addition, the amount of distilled water varied from 0.0001 kg/s to 0.000189 kg/s, while the EOC increases from 0.631 to 0.662.

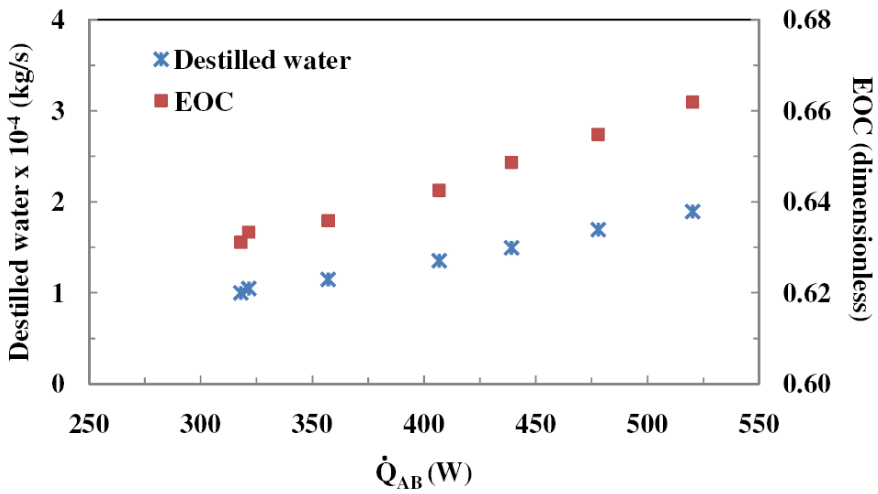


Figure 5. Distilled water mass flow rate and cogeneration efficiency vs. absorption heat load.

Figure 6 shows again the distilled water mass flow rate and *EOC*, but this time against the *COP*. Both parameters increase with the increment of the *COP*, which has a direct increasing relation with the increment of $\dot{Q}_{AB}$, as deduced from Eq. (5).

Figure 7 presents the electric efficiency and the EOC against the operating fuel cell temperature $T_{PEM}$. The electric efficiency $E_e$ remains constant when $T_{PEM}$ varied from 84.9°C to 88.4°C. However, the *EOC* shows slightly an increasing tendency with the increment of $T_{PEM}$. From this figure it can be observed that while $E_e$ is around 0.55, the EOC varied from 0.631 to 0.662. Furthermore, the efficiency of the proposed cogeneration system is about 21% higher than the normal fuel cell efficiency operating individually.

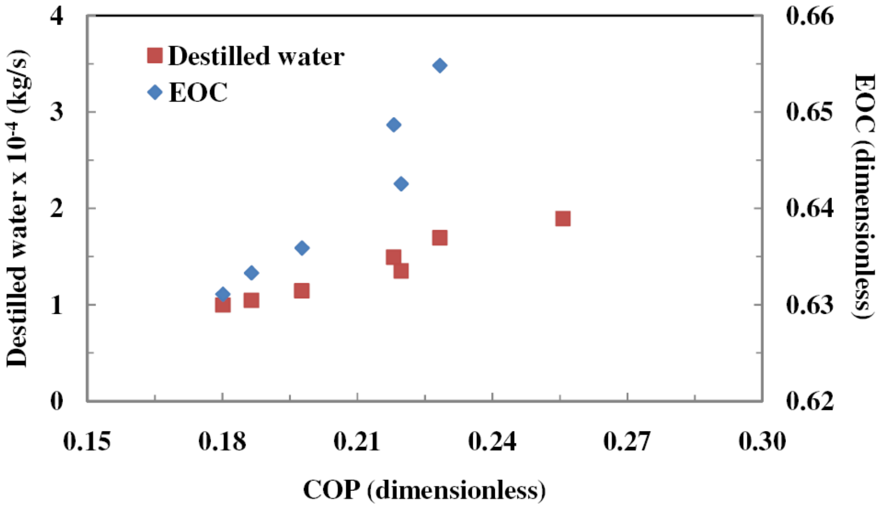


Figure 6. Distilled water mass flow rate and cogeneration efficiency vs. COP.

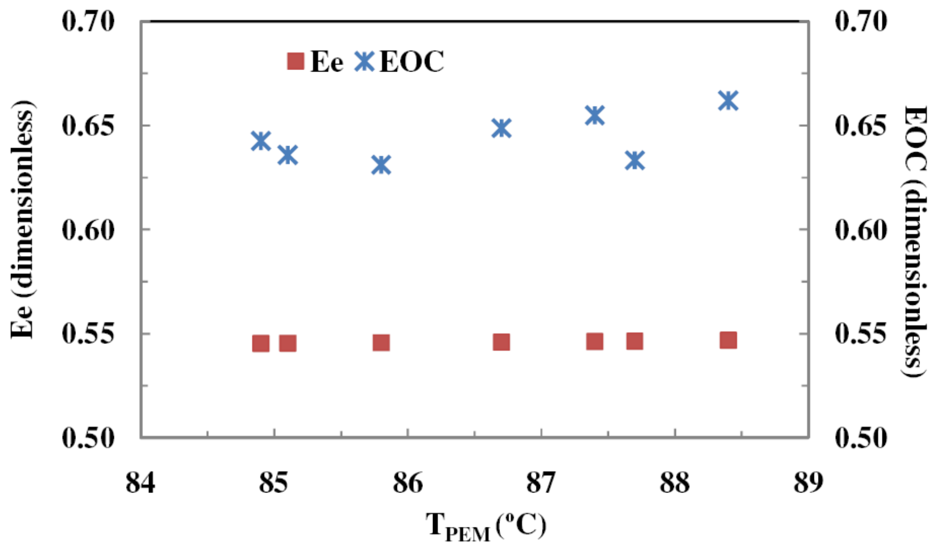


Figure 7. Distilled water mass flow rate and cogeneration efficiency vs. COP

The electrical power $P_e$, the available heat rejected by the PEMFC $P_t$, and the heat power used by the absorption heat transformer $\dot{Q}_{AHT}$ are plotted in Figure 8 as a function of $T_{PEM}$. The PEMFC generates a residual heat with suitable conditions to activate an absorption heat transformer coupled with a water purification system. The percentage of the heat rejected, which is used by the heat transformer ranges from 49.6% to 58.7%. Experimental results obtained at Center for Research in Engineering and Applied Sciences, located in the Autonomous University of state of Morelos, show that the experimental equipment can be activated with a quantity of energy ranging from 1723.7 W to 2093.2 W and temperatures from 84.9 to 88.4 ºC.

The waste heat from the PEMFC, applied to other thermal process increases the efficiency of energy use, as shown in Figure 7.

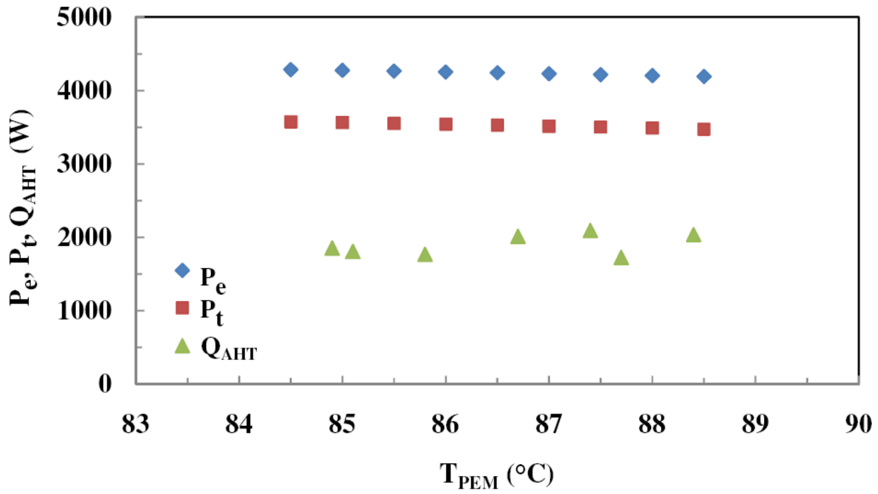


Figure 8. Heat used by the absorption heat transformer, electric power and heat power available vs. the temperature of the PEM fuel cell.

## 8. Conclusions

In this work, a novel cogeneration system formed by a proton exchange membrane fuel cell and an absorption heat transformer was analyzed. The results verify that the combined use of these systems is possible and suitable for electricity, heat and water distillation purposes.

The efficiency of cogeneration was defined for the coupling of the PEMFC with the water - LiBr AHT. The results of the simulation obtained through a thermodynamic model were used to perform experimental runs in order to estimate the performance parameters of the overall system.

The results illustrate increasing tendencies of efficiency of cogeneration *EOC* with increasing absorber heat load and COP. The electric efficiency $E_e$ remains practically constant with the increment of the operating fuel cell temperature, while the *EOC* shows slightly an increasing tendency.

The amount of distilled water varied from 1.0 x$10^{-4}$ kg/s to 1.8x$10^{-4}$ kg/s for an increasing absorber heat load and COP. In addition, the efficiency of cogeneration can reach values up to 0.662, which represent an increment of around 21% over the fuel cell efficiency operating individually.

The percentage of the heat rejected, used by the heat transformer ranges from 49.6% to 58.7% for the experimental conditions tested. Experimental results obtained demonstrate that the experimental equipment can be activated with a quantity of energy ranging from 1723.7 W to 2093.2 W and temperatures from 84.9 to 88.4 ºC.

## Nomenclature

| | |
|---|---|
| AHT | absorption heat transformer |
| PEMFC | proton exchange membrane fuel cell |

*Variables*

| | |
|---|---|
| COP | coefficient of performance |
| C | specific heat capacity of a liquid [kJ $kg^{-1}$ $K^{-1}$] |
| E | efficiency |
| EOC | efficiency of cogeneration |
| F | faraday’s constant [$9.65 \times 10^4$ C $mol^{-1}$] |

G gibbs energy [kg $kg^{-1}$]
H enthalpy [kJ $kg^{-1}$]
LiBr lithium bromide
P power [kW]
PEM proton exchange membrane
R gas constant [8.34 J $mol^{-1}K^{-1}$]
$\dot{Q}$ thermal power [W]
S entropy [$kJkg^{-1}{}^{o}C^{-1}$]
T temperature [ºC]

*Subscripts*
0 reference
AB absorber
EV evaporator
e electrical
GE generator
t thermal

*Greek letter*
η thermodynamic efficiency

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**Acknowledgements**

The support given by the Universidad Nacional Autónoma de México (UNAM) and Consejo National de Ciencia y Tecnología (CONACYT) through two postdoctoral fellowships is greatly appreciated. Also, the authors want to express their gratitude to the project PAPIIT-UNAM IN103409 for partial sponsorship of this study.