Hybrid fuel cell and geothermal resources for air-conditioning using an absorption chiller in Algeria

Wahiba Bendaikhaa*, Salah Larbib

aCentre de Développement des Energies Renouvelables, B.P. 62, Route de l’Observatoire, 16340 Bouzaréah, Algiers, Algeria
bDepartment of Mechanical Engineering, Ecole Nationale Polytechnique, 10, Avenue Hassen Badi BP 182 El-Harrach, 16200 Algiers, Algeria

Abstract

This Hybrid Energy System (HES) is mainly based on proton exchange membrane fuel cell (PEMFC) technology, which is supplied by a fuel reforming process for hydrogen production, starting from natural gas. The aim of this paper is to analyse the feasibility study of a process by combining a low-temperature geothermal source with a PEMFC subsystem (PEMFCS). This analysis allows the development of an onsite independent Hybrid Energy System used for air-conditioning, and especially the use of hot water for space cooling. PEMFC technology with an LiBr/H2O absorption system has been introduced to provide fresh air by a cooling process in a school canteen for 240 students, located in the western region of Algeria. The feasibility study shows that combining geothermal sources and PEMFC technology for air-conditioning production constitutes a promising solution.

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Keywords: PEMFC; Natural gas; Air-conditioning; Absorption chiller; Geothermal source; Thermal storage tank

1. Introduction

Stationary fuel cell based systems are designed to convert the chemical energy in a fuel into both electrical power and useful heat. In a residential application of combined heat and power (CHP) technology, a residential micro CHP system provides electricity and heat (space heating and hot water) for a building [1]. Fuel cell based stationary power generation technology is very promising because it is capable of achieving higher efficiencies, with lower emissions compared to conventional power systems.

* Corresponding author. Tel: +213-21-901503/901446; fax: +213-21-901560/901654.
E-mail address: w_bendaikha@yahoo.com
Furthermore, fuel cell residential systems have simple routine maintenance requirements, quiet operation, and low emissions compared to conventional systems [2].

In order to integrate a PEMFC into a stationary application, a fuel reformer, fuel cell stack with appropriate water-air and thermal management subsystems, inverter, power conditioner, and battery pack are necessary [3]. Natural gas appears to be the best fuel for hydrogen-rich gas production due to its favourable composition from lower molecular weight compounds [4–6]. The main technology for natural gas fuel reforming for PEMFC applications is steam reforming [7].

The country of Algeria, located in northern Africa, has very hot summers, particularly in the southern regions of the country. An increase in energy consumption is required in the summer due to cooling needs. Absorption refrigeration systems appear to be the solution to meet the energy requirements [8].

The aim of this paper consists in analysing a feasibility study by combining a low-temperature geothermal source with a PEMFC subsystem (PEMFCS), in order to develop an onsite independent Hybrid Energy System (HES) used for air-conditioning, and especially the using of hot water for space cooling. Conventional refrigeration systems, based on a vapour compression process, consume a lot of energy. In this study, we have introduced the PEMFC technology with a LiBr/H₂O absorption system to provide fresh air by a cooling process in a school canteen for 240 students located in the western region of Algeria. The sizing of the PEMFCS and the quantity of CH₄ consumed is estimated theoretically. The data used in this study are provided by the Solar Energy Potential Department of the Center of Renewable Energies Development (Algiers, Algeria).

2. Hybrid energy system description

The HES is based on several subsystems: the PEMFCS, two tanks for cooling and heating modes, a fan coil, and the LiBr/H₂O absorption chiller. Fig 1 shows the schematic representation of the studied HES. This system comprises two loops for maximum heat recovery; the first loop recovers heat from the geothermal source on the basis of a flat plate heat exchanger, while the second loop is used to recover heat from the PEMFCS on the basis of the second flat plate heat exchanger, which can boost the heat inside the thermal storage tank (TST) as shown in Fig. 1.

The HES application studied is for the canteen of a primary school for 240 students, located in the western region of Algeria, for cooling and heating modes.

In heating mode, hot water from the thermal storage tank (TST) is provided continually to the fan coil through a water circulating pump. Heating is assured by water with minimum temperature of 47°C [3].

In cooling mode, the outlet TST hot water valves were closed, the circulating pump coming from the TST is switched off, and TST hot water supplies the generator of the LiBr/H₂O absorption chiller, to produce chilled water at the evaporator.
As shown in Fig. 1, the absorption system comprises the generator, condenser, evaporator, absorber, and a solution heat exchanger. By supplying heat flow to the generator, the refrigerant (H\textsubscript{2}O) is separated from the absorbent (LiBr); it was conveyed to the absorber as a solution with low refrigerant content while water liberated from the solution in the generator through evaporation flowed to the condenser, where it was condensed to release heat. The difference in pressure caused a flow of the refrigerant to the evaporator where, at low temperature and low pressure, it evaporated and absorbed heat, which subsequently produced chilled water for cooling. The evaporated refrigerant was attracted by the absorbent in the absorber, where the refrigerant-rich absorbent solution was formed once more and was conveyed to the generator to start the whole cycle again [9].

The PEMFCS is modelled as a subsystem with methane as the input parameter and electricity and thermal energy as the output parameters [3]. The PEMFCS is cooled by the outlet hot water recovered by the geothermal source flat plate heat exchanger.

Empirical relations will be used to relate the fuel input to the electric and thermal energy outputs. The thermal to electric output ratios ($r_{TE}$) of the fuel cell subsystem are given by [3, 10]:

$$r_{TE} = 0.6801 \quad \text{for PLR} < 0.05$$

$$r_{TE} = 1.0785 \times \text{PLR}^4 - 1.9739 \times \text{PLR}^3 + 1.5005 \times \text{PLR}^2 - 0.2817 \times \text{PLR} + 0.6838 \quad \text{for PLR} > 0.05$$

where PLR is the part load ratio.
The complete PEMFCS electric efficiency is given by:

\[
\eta_{\text{electrical}} = 0.2716 \quad \text{for PLR} < 0.05 \tag{3}
\]

\[
\eta_{\text{electrical}} = 0.9033 \times \text{PLR}^5 - 2.9996 \times \text{PLR}^4 + 3.6503 \times \text{PLR}^3 - 2.0704 \times \text{PLR}^2 + 0.4623 \times \text{PLR} + 0.3747 \quad \text{for PLR} > 0.05 \tag{4}
\]

The cogeneration efficiency of the fuel cell subsystem can be expressed as:

\[
\eta_{\text{cogeneration}} = \eta_{\text{electric}} + \eta_{\text{thermal}} = \eta_{\text{electric}} (1 + r_{TE}) \tag{5}
\]

The total thermal energy available from the PEMFCS to be used in the canteen is determined by the heat transfer rate [3, 9]:

\[
\dot{Q}_{FC} = r_{TE} \dot{E}_{FC} \tag{6}
\]

where \( \dot{E} \) is electrical power. Knowing \( E_{FC} \), the fuel used is calculated from:

\[
F_{FC} = E_{FC} / \eta_{\text{electric}} \tag{7}
\]

The TST temperature as a function of time is given by [10]:

\[
T_{TS,t_2} = \frac{\alpha}{\beta} + \left( T_{TS,t_1} - \frac{\alpha}{\beta} \right) \exp \left( -\frac{3600 \beta}{m_{TS} C_p} (t_2 - t_1) \right) \tag{8}
\]

where \( C_p \) is the specific heat, and

\[
\alpha = r_{TE} \left( \dot{E}_{\text{pump}} + \dot{E}_{\text{Light}} + \dot{E}_{FC} \right) - \dot{m}_{HW} C_p \left( T_{HW} - T_{CW} \right) + U_L A_L T_{zone} \tag{9}
\]

\[
\beta = U_L A_L \tag{10}
\]

where \( \dot{m} \) is the mass flow rate, and \( U \) the overall heat transfer coefficient. The numerical simulation of the HES shown in Fig. 1 is based on data related to the 100 m² area of the school canteen.

3. Data presentation

Algeria has important geothermal resources which have not been completely explored. In the northern region of the country, more than 200 hot springs are listed with a discharge temperature ranging from 22°C to 98°C (Fig. 2). The hottest springs are at 68°C in the western region (Hammam Bouhanifia), 80°C in the central region (Hammam El Biban), and Hammam Chellala with 98°C for the eastern region, as shown in Fig. 2 [11].
The Hybrid Energy System is situated in Saïda city NW of Algeria. The real data of typical day for ambient temperatures evolutions in cooling and heating modes as function of time are shown in Fig 3(a). The rush hour of the canteen is by 12 to 2 pm, so in heating mode, the temperature in this period is about 6 °C whereas in cooling mode it is about 27.5 °C, so the air-conditioning is necessary.

Fig. 3(b) shows the HES electrical consumption in cooling and heating modes for the rush hour of the canteen over 50 minutes. It depends on the working mode. The part load ratio (PLR) shows the canteen electrical consumption compared to the peak power operation. It can be seen that in cooling mode, the energy demand increases slightly due to the electrical consumption of the absorption chiller pumps.

In cooling mode, the maximum electrical load demand is 3.5 kW. In heating mode, the maximum load demand is 3.03 kW; this corresponds to the pumps, fan coil, and lamps consumption in the rush hour in the canteen.

4. Simulation results

The Hybrid Energy System has been studied theoretically, but the heat recovery from the geothermal well by the flat plate heat exchanger (loop 1) was studied experimentally [3]. In this case, the flat plate
heat exchanger (heat recovery subsystem) operates in heating and cooling modes, and the inlet TST hot water is transported by isolated tubes to the fan coil located in the canteen at a distance of 17 m.

The experimental results for the flat plate heat exchanger operation with heat recovery from the geothermal well at 47°C are shown in Fig. 4.

![Fig.4. Operation of the flat plate heat exchanger (heat recovery subsystem) in loop 1 [3].](image)

Point (1) expresses the inlet hot water coming from the geothermal well (47°C); the curve gives us a temperature of 44.5°C. It can be seen that the TST temperature (point 2) reaches the geothermal water temperature of 45°C in 40 min, and keeps it for all the operation time. Point (3) is the outlet hot water coming from the first loop toward the second loop, which is at approximately 36°C. This water is pumped through the PEMFCS heat exchanger and returned to the TST at higher temperature (57°C), as can be seen in Fig. 5(a). Point (4) is the outlet TST hot water; it is initially at 30°C, and reaches 44°C in 40 min.

![Fig.5. (a) Thermal storage tank (TST) temperature evolution versus time for heating and cooling modes in the second loop. (b) Chilled water temperature in cooling mode.](image)

Fig. 5(a) shows the PEMFCS and TST temperature evolution versus time after 40 min of heat recovery from the first loop (see Fig. 1). It can be seen that the PEMFCS temperature is transferred to the TST with heat recovery by the second loop (Fig. 1). When the TST temperature increases, the PEMFCS temperature decreases until it becomes close.

The TST temperature improves in the second loop with PEMFCS heat recovery, which can reduce the chilled water temperature, as can be seen in Fig. 5(b). When the TST temperature reaches 50°C, the chilled water temperature is 11°C, see Fig. 5(b); it decreases as a function of increasing TST temperature.
Methane consumption is calculated by eq. (7); it increases with the increase in the electrical loads of the canteen. In cooling mode, at maximum power of 3.5 kW supplied by the PEMFCS, see Fig. 3(b), the amount of methane is 0.05 kmole/h. In heating mode, the amount of methane consumed is less than in cooling mode (0.042 kmole/h), because it was more electrical loads due to the additional pump consumption of the absorption chiller.

Fig. 6(b) shows HES efficiency; it can be seen that in heating mode the efficiency is about 70%, and in cooling mode it varies by 30–45%. The HES is more efficient in heating mode because all the heat recovered is used for space heating, but in cooling mode, the heat is used in the absorption system for cooling.

5. Conclusions

In this paper, a feasibility study of integrating a PEMFC into air-conditioning system using a geothermal source and LiBr/H₂O absorption system was achieved for cooling and heating modes.

The simulation results show that Hybrid Energy System efficiency is more important in heating mode (70%), because all the heat recovered in the thermal storage tank is pumped to the fan coil for heating the canteen. In cooling mode, the heat recovered is used in the generator of the absorption system to operate in cooling mode, so the efficiency drops (30–45%). At maximum PEMFCS electrical power (3.5 kW), the methane consumed is 0.05 kmol/h.

The feasibility study shows that using the geothermal resources and a low-temperature PEMFC for air-conditioning is a promising solution to create independent energy systems to supply isolated sites from the electrical grid with high efficiency.

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