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Article

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Towards performance assessment of fuel cell integration into buildings

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Abstract

The integration of Combined Heat and Power (CHP) systems, especially fuel cell systems, into buildings have attracted a lot of interest these last years. It is due to their higher efficiency, cleanliness and their capability for producing both valuable thermal energy and electricity, from a single source of fuel, such as natural gas or hydrogen. Their high efficiency, which can reach 85%–90%, leads to a decrease in both greenhouse gas emissions and costs when compared to the conventional methods of generating heat and electricity separately. The aim of this work is towards efficient integration of a Proton Exchange Membrane (PEM) fuel cell into buildings in order to supply it with both electricity and heat. Experiments on a system composed of fuel cell, converter, and hydrogen tank have been carried out and compared to the simulations conducted using Matlab/Simulink where the system's model has been developed. Simulation and experimental results are compared in order to show the accuracy of the models that have been developed and the efficiency of the fuel cell when operating as a CHP system to supply the building with both electricity and heat.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

Keywords: CHP system; Fuel cell; Hydrogen; Matlab/Simulink softwares

1. Introduction

The integration of fuel cells into buildings have caught a lot of attention these last years due to their higher efficiency, which can reach 85%–90%, low noise level, cleanliness, modularity and their ability to generate both valuable thermal energy and electricity, from a single source of fuel, such as natural gas or hydrogen [1]. Their high efficiency leads to a diminution in both greenhouse gas emissions and costs when compared to the conventional systems of producing heat and electricity separately [1]. Fuel cells could be used as Combined Heat and Power

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(CHP) systems, known as cogeneration, (e.g., reciprocating engines, micro-turbines, stirling engines, fuel cells) for producing both electrical and thermal energy simultaneously [1,2]. Concerning the micro-cogeneration applications, fuel cells and Stirling engines are the most used due to their capability of utilizing sustainable fuels (e.g., natural gas, regenerative biomass, hydrogen), which makes them environmentally respectful [2].

Fuel cell is constituted of an anode, a cathode, and an electrolyte. It is an electrochemical device that converts directly the chemical energy of the exothermic reaction between hydrogen on the anode side and atmospheric oxygen on the cathode side, accompanying with the flow of hydrogen ions through the electrolyte and the electrons via an external circuit, into electricity while releasing heat [2]. The speed of the reaction depends on the electrolyte and the catalyst used [2]. Also, the fuel cell needs some auxiliary components for its operation, such as, valves and fans for cooling. Furthermore, there are several types of fuel cells, which are classified according to the electrolyte, the operating temperature and the fuel used, such as Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC), Direct Methanol Fuel Cell (DMFC), Sulfuric Acid Fuel Cell (SAFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC), Solid Polymer Fuel Cell (SPFC) and Proton Exchange Membrane Fuel Cell (PEMFC) [2]. The differences between all types of fuel cells, such as, the used electrolyte and the operating temperature, are reviewed by Alanne and Saari [2]. The most appropriate fuel cells for micro-cogeneration applications are the low temperature PEMFC operating around 80 °C, and the high temperature SOFC that operates in the range of 600–1000 °C. Though, the PEMFC, which is constituted by two platinum catalyzed porous electrodes (i.e., anode and cathode) separated by a solid polymeric membrane electrolyte, still the most used for micro-cogeneration applications due to its multiple advantages (e.g., Low temperature, Quick start-up and load following, less corrosion, high power density) compared to the SOFC [3].

The work reported in this paper is a part of an ongoing project, named MIGRID, which aims to set up an MG system for the purpose of testing some approaches, such as dimensioning and control, and comparing simulations to experiments in order to validate the components' models [4,5]. Currently, the MG system that we have in our EEBLab (Energy Efficient Building testing Lab), is composed of PV panels for electricity production from solar radiation, wind turbine to produce electricity from the wind, batteries to store the excess produced electricity for operating the appliances when there is no production, regulator to regulate the charge and the discharge of the batteries, inverter to convert the direct current (DC) to alternative current (AC), AC/DC converter to convert the AC received from the wind turbine into a DC, and finally the electric grid for supplying electricity to the building when there is no production and the batteries are empty. As a perspective, we want to integrate also a fuel cell into our EEBLab in order to supply the building with both electricity and heat, so we can minimize the consumption of the HVAC (Heating, Ventilation and Air-Conditioning) and thus diminishing the electricity needed by the building. Therefore, the aim of this work is towards efficient integration of a PEM (Proton Exchange Membrane) fuel cell into our EEBLab test-bed in order to supply the building with both electricity and heat. For that, simulations and experiments of the system must be performed in order to evaluate its performance and effectiveness. Thus, simulations using Matlab/Simulink and experiments of the system, which is composed of PEM fuel cell and DC/DC converter, have been carried out and compared in order to show the accuracy of the developed models and the efficiency of the fuel cell when operating as a CHP system to supply the building with both electricity and heat.

Concerning the converter's model, it has been reported with more details in our foregoing work presented in [5]. Regarding the fuel cell, several mechanistic models [6] and empirical models [3,7] have been developed by the research community in order to evaluate its behavior and performance and predict its current/voltage relationship. Therefore, the system was simulated and experimented, and then evaluated in order to figure out its behavior and performance. The remainder of this paper is structured as follows. The system's description, modeling and experimentation are reported in Section 2. Section 3 presents the obtained simulation and experimental results. Finally, the conclusions and perspectives are given in Section 4.

2. System's description, modeling and experimentation

The diagram of the proposed system is illustrated in Fig. 1. It is composed of a 1.2 kW PEM fuel cell to produce both electricity and heat, a hydrogen tank to supply the fuel cell by the needed hydrogen, and a DC/DC converter to stabilize the fuel cell's voltage so it can be connected to the DC loads.

The purpose of this system is to show the behavior and the performance of the fuel cell when operating as a CHP system in order to supply the building with both electricity and heat. Therefore, the work presented in this paper focuses on the modeling, simulation and experimentation of this system. Thus, the system has been modeled and

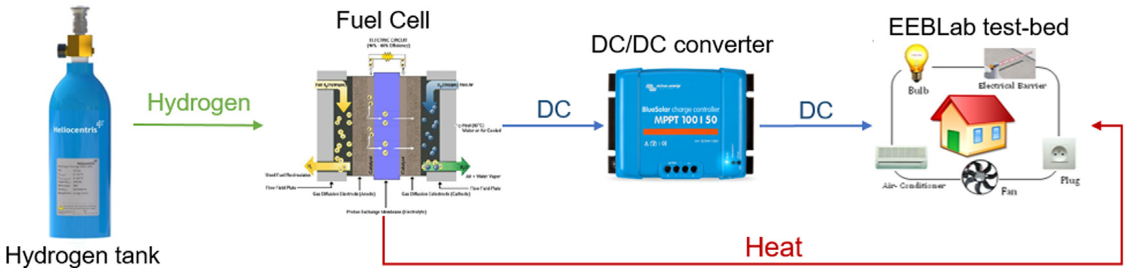

Fig. 1. System's architecture.

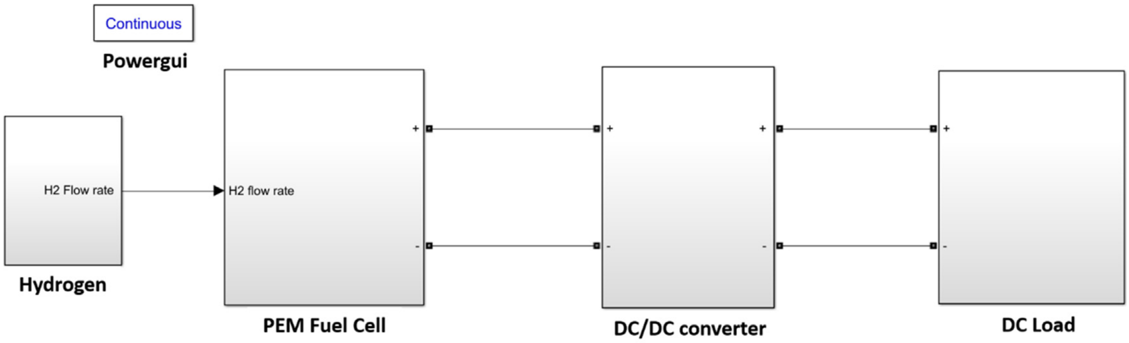

Fig. 2. System's Simulink model.

simulated under Matlab/Simulink using similar experimental conditions (e.g., hydrogen flow rate, load consumption, temperature) (see Fig. 2).

Concerning the DC/DC converter, it is used for stabilizing the fuel cell's output voltage so it can be connected to the DC load. Three types of DC/DC converter exist: the buck converter, the boost converter, and the buck–boost converter. The difference between the three types is that the ratio between the input and output voltage can be higher or lower than 1. The model used in this paper have been already developed and described with more details in our previous work [5]. Regarding the fuel cell, we have used the model developed by Njoya et al. [7] in order to evaluate its behavior and performance, and estimate the amount of power produced by it. Furthermore, we have computed and estimated the amount of produced heat using the enthalpy change ΔHr of the reaction, which is equal to -285.84 kJ/mol of H_2 when the produced water is a liquid. The enthalpy change is negative because the reaction is exothermic (i.e., the energy is released). It is defined in terms of the Gibbs free energy ΔG and the entropy ΔS as follows [8]:

$$\Delta H_r = \Delta G + T\Delta S \tag{1}$$

A part of this enthalpy is responsible for the vaporization of water (ΔH_{vap} = 44.01 kJ/mol), another part, which is equal to (-237.2 kJ/mol of H_2), is the Gibbs free energy ΔG that can be defined as useful energy (i.e., the maximum produced energy by the fuel cell), and finally, the remaining part, which is equal to (-4.63 kJ/mol of H_2), is the term $T\Delta S$ that represents the energy, which is converted directly into heat. Consequently, only a fraction of the enthalpy is usable as electricity and heat, however, most of it cannot be exploited since it is lost on increasing the temperature of the fuel cell (e.g., frame, electrodes and electrolyte) and the hydrogen gas. The amount of heat, which is lost, is calculated using the following equation, where m is the component's density (kg/m^3), C_p is the specific heat capacity (kJ/kg K), and T_{final} (resp. $T_{initial}$) is the final (resp. the initial) temperature of the experiment (K).

$$Q = m * C_p * (T_{final} - T_{initial}) \tag{2}$$

In order to compare simulation and experimental results for the purpose of validating the models, the system has been also experimented, as illustrated in Fig. 3. The system is composed of hydrogen tanks, a 1.2 kW Nexa

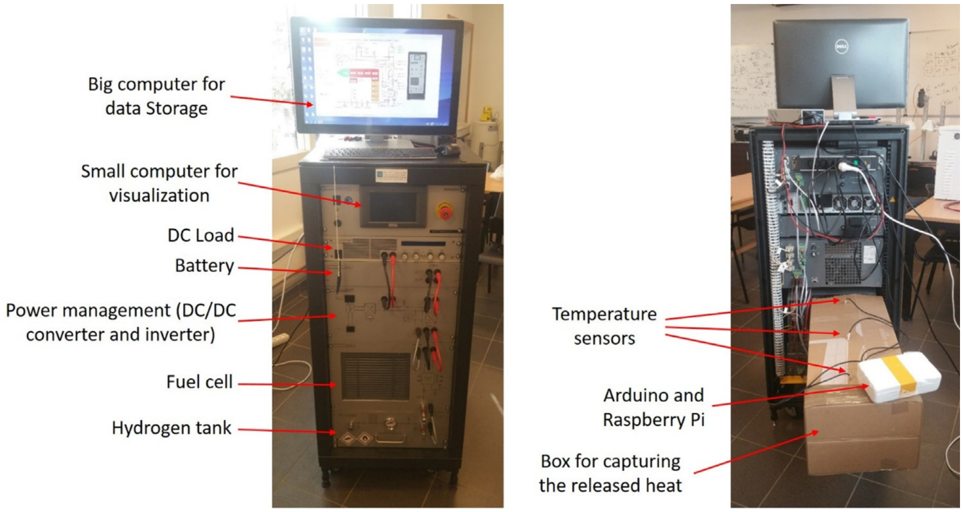

Fig. 3. The deployed system for experimentations.

PEM (Proton Exchange Membrane) fuel cell manufactured by Heliocentris, DC/DC converter, inverter in case we have an AC load, batteries to supply electricity to the small computer, which is used for visualizing the monitored data (e.g., fuel cell's current and voltage, stack temperature, hydrogen flow rate), and finally a DC load. Besides, we have added a box to the system in order to capture and compute most of the generated heat in a finite volume of approximately 0.0478 m^3. An IoT/Big Data platform [4] composed of three temperature sensors, which are connected to an Arduino board, was also deployed in order to measure the temperature in the box, so we can compute the amount of the generated heat. The gathered data are sent via a Raspberry Pi to a cluster for processing and storage, and then, are visualized and extracted using a web application that have been already developed.

The released heat is calculated using Eq. (3) [9], where ρ_{air} is the air's density (kg/m^3), V_{air} is the volume of the air trapped in the box (m^3), $C_{p,air}$ is the specific heat capacity (kJ/kg K).

$$Q = \rho_{air} * V_{air} * C_{p,air} * (T_{final} - T_{initial}) \tag{3}$$

3. Simulation and experimental results

Several simulations and experiments have been conducted in order to study the electrical behavior of the fuel cell and to analyze its performance. The stack's temperature (Fig. 4a), which reaches 50 °C, and the H_2 flow rate entering into the fuel cell, which is around 5.92 nl/min, have been measured and used as inputs to our system. As a result, and as depicted in Fig. 4(b), the resistive load that we have used consumes approximately 480 W, and the measured power at the outlet of the fuel cell is around 503 W. The difference between the load's power and the fuel cell system's power, which is around 20 W, is consumed by the auxiliary components that are necessary for the operation of the fuel cell. Furthermore, in the simulation, we have considered the maximum efficiency of the fuel cell system as 50% [10], while knowing that the reference electric power (P_R) given by the manufacturer for an efficiency of 50% is 600 W. The difference between the simulated fuel cell system's power and P_R does not reach 10% (see Fig. 4b), which validates the adopted model. These values show that the fuel cell system provides only 80%–85% of its maximum power. It is still capable of delivering more than 80 W of power when needed. However, it is more suitable for the operating power of the fuel cell system to be well below its maximum power [11].

Furthermore, we have used the change in the enthalpy in order to compute and estimate the amount of the generated heat. Thus, using the hydrogen flow rate that we have converted into mol/min and the efficiency of the system, which is approximately 50%, we found that approximately 33.58 kJ/min of heat is generated. As a result, the total amount of the generated heat during all the experiment is 380.46 kJ. However, only a fraction of this energy is released outside (i.e., the energy that could be used for heating the building) since most of it is lost on increasing the temperature of the fuel cell (e.g., frame, electrodes and electrolyte) and the hydrogen gas. The amount of heat

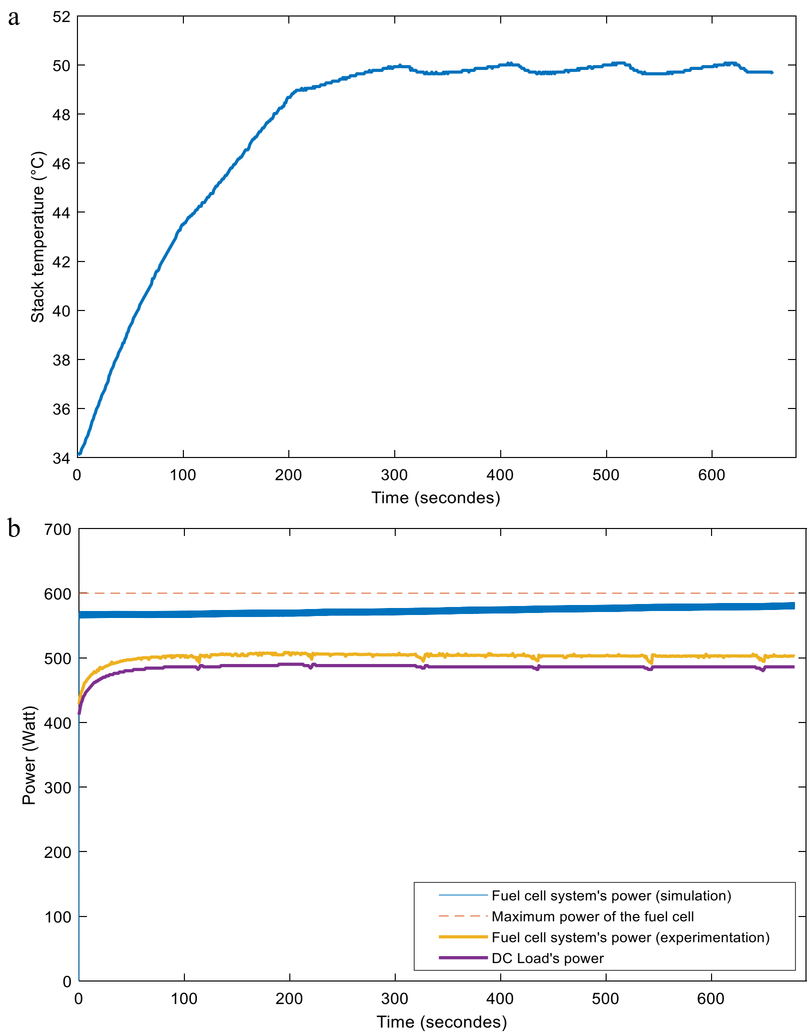

Fig. 4. (a) The stack temperature; (b) Simulation and experimental results.

consumed by the fuel cell in order to increase its temperature, which is around 379.14 kJ, is calculated by using eq. 2 using the fuel cell's mass (22 kg), the stack's temperature (Fig. 4a), and the average specific heat capacity of all the fuel cell's components (0.881 kJ/kg K for the frame and 1.32 kJ/kg K for the electrodes and electrolyte). Also, the amount of heat used to preheat the hydrogen, which is around 0.0268 kJ, is calculated by using eq. 2 using the hydrogen flow rate that we have converted into Kg/min, the specific heat capacity of hydrogen (10.140 kJ/kg K), and the variation of the hydrogen's temperature that does not reach 0.5 degree. Therefore, the amount of heat that could be released outside is approximately 1.2930 kJ.

In order to compare the abovementioned results to the experimental ones, we have measured the temperature in the box, which we have added to the system, in order to have an idea about the evolution of the temperature, and thus the released heat by the fuel cell. Fig. 5 depicts the evolution of the temperature in the box (the average values of the three integrated sensors). Therefore, the released heat by the fuel cell is calculated by using Eq. (3) using an air's density of 1.2 kg/m^3 (we supposed that the air's density does not change with temperature), the volume of the air trapped in the box is 0.0478 m^3, the air's specific heat capacity is taken equal to 1.005 kJ/kg K, and the variation of the temperature during the experiment (K). As a result, we found it approximately equal to 1.265 kJ. As a conclusion, the results of both the theory and the experiment are approximately similar. The small difference between both of them could be caused by the fact that the box is not totally isolated, the measurement noises and

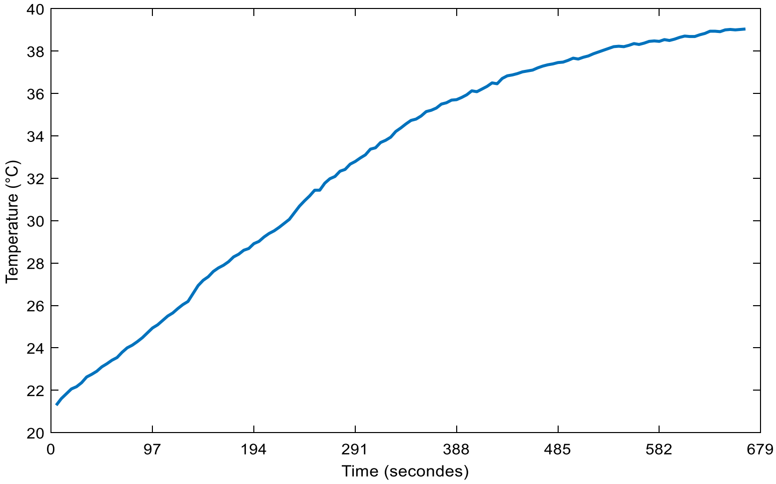

Fig. 5. The evolution of the air temperature in the box.

the lack of stability of the sensors used in the experiments or likely by do not taking into account the variation of some parameters with temperature (e.g., air's density).

4. Conclusions and perspectives

In this work, we have focused on the modeling, simulation and experimentation of the fuel cell in order to evaluate its behavior and performance. Simulations and experiments have been carried out and results have been reported and compared in order to show the accuracy of the developed models as well as the efficiency of the fuel cell when operating as a CHP system to supply the building with both electricity and heat. The results of both simulations and experiments are approximately similar, thing that validate the developed models. Our ongoing work puts more emphasize on its integration within our deployed micro-grid together with more simulations and experiments. The performance of the whole system will be assessed in terms of energy and heat production efficiency.

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