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Combined heat and power using high temperature proton exchange membrane fuel cells for comfort applications

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Abstract

Global concerns about nowadays' energy shortage problems as well as climate change effects have encouraged alternatives to classical energy sources such as fossil fuels and nuclear power plants. In this context, combined heat and power is presented as a useful option due to its ability of generating both electrical and thermal energy more efficiently than conventional methods. Regarding this, high temperature proton exchange membrane fuel cells are not only a reliable way of implementing combined heat and power systems, but also a better solution in terms of energy conversion efficiency and greenhouse gases emissions reduction. Therefore, high temperature proton exchange membrane fuel cells are being installed around the world and policies encouraging its utilisation are being promoted.

Keywords:
Fuel cell, Combined heat and power, Automatic control.

1. Introduction

Among modern world's main issues, potential energy shortage for the years to come and climate change consequences are some of the main ones according to several institutions around the globe. Primary energy consumption has been increasing at a rate of 2.5% recently (H.R. Ellamla, 2015). According to the same studies, coal consumption has even increased in recent years with a maximum of 29.9% of global primary energy in year 2012. At the same time, the aftermath of the earthquake and its consequent tidal wave (year 2011) in Fukushima's nuclear power plant, Japan, encouraged the government in that country to reduce the countries dependence on nuclear energy by 89% (6.9% around the world). Taking into consideration that efficiencies achieved by coal-fired power plants can reach 41% it has been stated that reducing heat waste rate is one of the aims for the future to come.

This state of events is forcing political authorities around the world to seek for new ways of supplying energy which manage waste energy properly. For residential uses the energy consumption can be classified as 27% of electrical energy and 38% of thermal energy around the world. Depending on the country, different purposes for this energy are defined, as seen in Fig. 1. In this context, combined heat and power (CHP) has arisen as an option for years to come due to its ability to make both electrical and thermal energy generated profitable. Among the different kinds of CHP technologies, fuel cells are one of the main options being proposed by several governments as a way of changing part of the world's energy generating system. This article focuses specifically on high temperature proton exchange membrane fuel cells (HT-PEMFC) and, more precisely, the chemical and physical principles behind them and their technical specifications.

In this article different some fuel cell technologies under study and the physical principles behind them are presented. Afterwards, the technical components of these cells are classified, as well as the desired control objectives. Regarding combined heat and power systems, its advantages, stages and working procedures are described, as well as some of the applications for these kind of systems. Finally, the usage of com-

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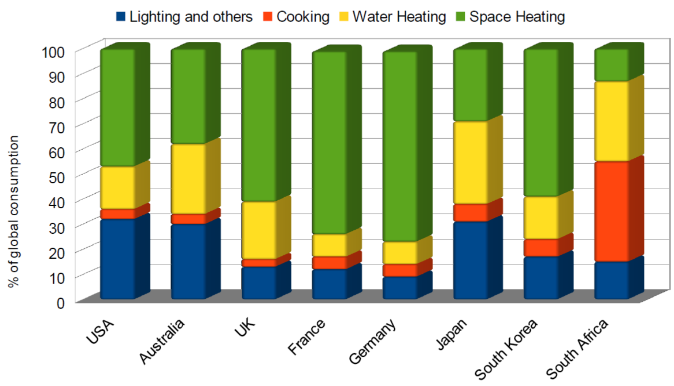

Figure 1: Residential energy usage in different countries (H.R. Ellamla, 2015)

bined heat and power with high temperature proton exchange fuel cells for comfort applications, i.e. residential uses, is addressed.

2. Fuel cell technologies

A fuel cell is defined (D. Hissel, 2016) as an electrochemical converter which continuously converts the chemical energy from a fuel and an oxidant into electrical energy, heat and other reaction products. Both fuel and oxidant are continuously supplied at the same pace they are being consumed. Each cell is composed of different layers, presented as follows:

- *A porous anode*: located in the left hand side of Fig. 2. Gaseous fuel diffuses through the pores of the anode to reach the interface with the electrolyte able to conduct ions, where it is oxidised; electrons are conveyed from the anode to the cathode by an external circuit.
- *A porous cathode*: located in the right hand side of Fig. 2. The gaseous oxidant (oxygen) diffuses through the pores of the cathode to reach the interface with the electrolyte, and is reduced.
- *An electrolyte*: the middle part of Fig. 2, which conducts the ions from one electrode to the other.
- *The bipolar plates*, in all channels in Fig. 2, which convey the reactants to the electrodes, evacuate the reactants in excess, the product of the reaction (mostly water), and the heat produced by the cell.

All these layers are sealed using silicon to prevent hypothetical gas and cooling fluid leakages and constitute the so called stack of layers.

2.1. Fuel cell characteristics

A proton exchange membrane fuel cell (PEMFC) has an anode which is fed with pure hydrogen (H_2) and its cathode with pure or ambient air oxygen. Hydrogen is oxidised at the anode and consequently H^+ (protons) flow across the polymer membrane from anode to cathode. Simultaneously, the cathode is fed with electrons collected by the bipolar plates. At the cathode, oxygen, electrons and protons meet to produce water (Fig. 2). The chemical reactions are

$H_2 \longrightarrow 2\,H^+ + 2\,e^-$,

$\frac{1}{2}\,O_2 + 2\,e^- + 2\,H^+ \longrightarrow H_2O$.

This process leads to the production of electric power, thermal power and water. The electrolyte is a polymer which conducts protons only if it is well hydrated. This process is depicted in Fig. 2.

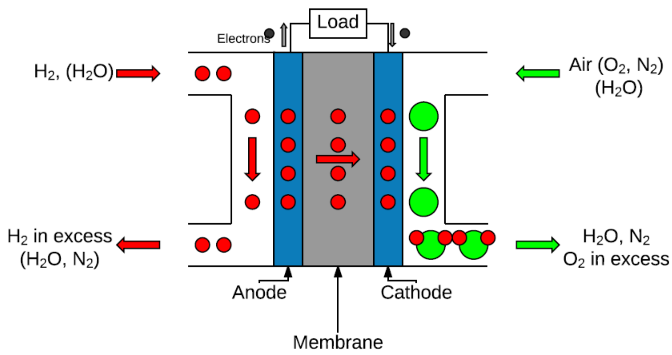

Figure 2: Fuel cell scheme

Neglecting the cell process losses, the reversible Nernst potential E_N across the cell is defined by:

$$E^0 = -\frac{\Delta g_f^0}{2F}, \tag{1}$$

$$E_N = E^0 + \frac{RT}{2F} ln\left(\frac{P_{H_2}}{P_0}\right) + ln\left(\frac{P_{O_2}}{P_0}\right), \tag{2}$$

where

- $\Delta g_f^0 = -228.59\,kJ/mol$ is the Gibbs free energy to form a mole of vapor water.
- $R = 8.31\ J/(K \cdot mol)$ is the ideal gas constant.
- T is the temperature.
- P_{H_2} is hydrogen's partial pressure.
- P_{O_2} is oxygen's partial pressure.
- P_0 is the atmospheric pressure.

The above mentioned reaction is exothermic and the released heat Q_r is related to the process entropy ΔS as follows:

$$Q_r = T\Delta S. \tag{3}$$

Real fuel cells present, however, cell voltage decreases when compared to the Nernst reverse voltage E_N with or without load. The main cause of this decreasing is the cell's losses. These issues can be described as follows:

- The activation of the redox reactions, especially when the current is low.

- The ohmic resistance due to ion transport through the membrane, the electrodes and the bipolar plates. The one caused by the bipolar plates can be generally neglected.

- The concentration voltage drop due to the transport of matter through the porous electrodes and more specifically through the gas diffusion layer, which is dominant at high current. These are closely related with the current I, usually expressed as related to the electrode area S by using the current density j, as it can be seen in Eq. (4).

$$j = \frac{I}{S}. \tag{4}$$

2.2. Advantages of HT-PEMFC

While low temperature fuel cells (LT-PEMFC) operate at 60-80°C, the high temperature ones (HT-PEMFC) work at a range of temperatures between 120°C and 200°C. Differences when comparing LT-PEMFC and HT-PEMFC are the following ones:

- At low temperatures several issues regarding liquid water and its distribution throughout the system are key points to be considered. This problem disappears when the temperature exceeds the water boiling temperature, which is the case of HT-PEMFC technologies.

- LT-PEMFC present overpotential at the cathode responsible of cell voltage loss because of slowing of the electrochemical kinetics on the cathode side.

- Platinum catalysts used to improve the electrochemical reaction have a particular affinity for carbon monoxide (CO). A high concentration of CO (above 10 ppm) affects the performance since it may poison the platinum electrocatalyst.

- Requirement of pure hydrogen (99.999%) and the economical issues caused by the hydrogen purifying process. Hydrogen obtained from reforming can be used for HT-PEMFC due to its acceptance of impurities and reduce the power production cost consequently.

- HT-PEMFC have different charge transfer and proton transfer with temperature due to the resistance reduction as temperature is increased. As a result, the kinetic reaction in the fuel cell is more effective, improving the global efficiency of the fuel cell as a whole.

- Temperatures higher than 140°C allow a higher tolerance of CO, as shown in Figure 3.

In the case of low temperature fuel cells, although several improvements have been applied in order to try to reduce the CO effect in low temperature fuel cells such as feeding oxidants into the fuel, advanced purification of the reformate gas, more CO tolerant catalysts or modifying the electro-catalyst, the problem has not yet been eradicated. Because of that, high temperature fuel cells are a better solution to prevent catalyst poisoning.

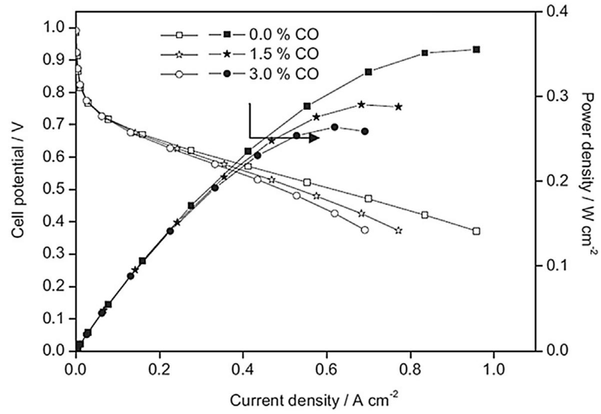

Figure 3: Polarization and power density curves at 160°C and 180°C for three different anode fuel types reproduced from (R.E. Rosli, 2016)

2.3. Control objectives for HT-PEMFC systems

When studying fuel cells, several aspects are being taken into consideration. Among these aspects, the studied ones are:

- *Energy efficiency*: the main effort is driven towards reducing energy losses and avoiding extra internal consumption.

- *Lifetime*: a diagnose of the main causes of deterioration of the fuel cell systems.

For this reason, a control optimization index including terms for both fuel cell efficiency and lifetime need to be included. Both properties are related and can not be optimised separately. For instance, if during a fuel cell system operation a certain operation point to maximise efficiency is selected, a low electrical current should be selected, which would imply a high voltage on the cell. This high voltage affects the mechanical elements of the fuel cell thus reducing its lifetime expectancy. That is the reason why a combined optimization needs to be done.

3. Combined heat and power systems

Combined heat and power (CHP) using fuel cells is one of the main applications of this kind of technologies. The structure includes several units such as compressors, heat exchangers, electrical converters and transformers. CHP systems redirect several heat flows generated in order to produce both heat and electrical power. An example of the system is the one depicted in Figure 4.

Fuel cells can be used for applications requiring from hundreds of milliwatts (mW) to megawatt (MW) of electrical power. Fuel cell combined heat and power systems (FC-CHP) include the following elements:

- *Fuel cell stack*: constituting a group of fuel cells, whose quantity may differ depending on the desired output power. Each fuel cell characteristics are as described previously in this article.

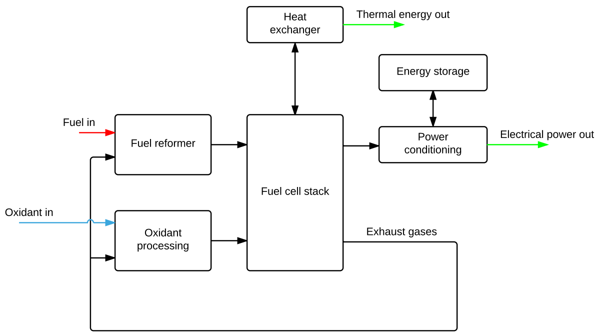

Figure 4: CHP system diagram

- *Fuel processor*: responsible of converting fuel such as natural gas or methanol into a hydrogen-rich stream to supply the fuel cell stack. The hydrogen must be as pure as possible to enhance efficiency.

- *Heat exchanger*: thermal management options for PEMFC depend on the operating and exhaust air temperatures. HT-PEMFCs' heat is processed using a a cooling system, which can be internal or external. The heat recovered from a PEMFC stack can be used both for space heating and for hot water production. In a PEMFC system an after-burner (used to burn unreacted fuel) can also be employed to create a higher heat output and to increase the overall efficiency. The cathode air excess and the unconsumed fuel in the stack are combusted in a burner and the produced heat is used for preheating the reactants supplied to the reformer or the fuel cell stack. Large quantities of air are required for reactant air preheating and for cooling. Industrial air blowers are generally inefficient and can consume significant amounts of power, taxing the system's electrical efficiency. Low-cost heat exchangers are desirable for heating or cooling of various gas streams with CHP systems.

- *Power conditioning system*: its purpose is converting the continuous current released by the fuel cell stack into energy with the required characteristics (continuous, alternating, specified voltage levels, etc.). For this reason, several power electronic converters and transformers may be used.

4. CHP-HT-PEMFC Applications

Combined heat and power (CHP) or cogeneration in general can be found in all kind of systems around the world, due to its efficiency when producing both heat and electrical power simultaneously. Research being carried on in the field has empowered governments and companies to think of these systems as an option for new systems and, most specifically, for replacing certain conventional energy generation systems. More precisely, HT-PEMFC are being applied in several ways and fields (R. Hite P.E., 2009). These are often classified in stationary and non-stationary applications, understanding non-stationary as those for transport systems:

- *Non-stationary applications*: due to its size and relatively low weight, PEMFC are a valid alternative to conventional vehicle powering methods. Vehicle powering using HT-PEMFC (Y. Liu, 2016) is especially used nowadays in buses and also in hybrid vehicles.

- *Stationary applications*: residential heat and power generation, trying to be an alternative to conventional generation of heat and electrical power separately through the gas and electrical public distribution grids. Other stationary applications are industrial ones like wine industry. Finally, another option is using this kind of fuel cells for emergency systems implemented in hospitals, data centres or scientific facilities, among others.

Among all applications enlisted, comfort applications for residential uses have been a key policy adopted by several governments around the world (H.R. Ellamla, 2015).

5. Research plan

The main research plan is modelling both HT-PEMFC and the whole CHP system using fluid dynamics and heat transfer equations. Once these models are obtained suitable control algorithms will be implemented.

The first level to be studied will be the fuel cell itself, described by fluid dynamics and heat transfer partial differential equations in the literature (Y. Ju, 2005; Y. Shan, 2005). These fluid dynamics equations should include time dependencies as well as dimensional constraints. After that, a suitable operation point will be chosen in order to implement a low level control strategy. The second level to be considered is the one of the whole CHP system and its coordination control.

Finally, the global energy management strategy will be defined from a higher level and its main goal is ensuring efficiency and lifetime optimisation. For this reason, using model predictive control and using information from previous states during the system operation will be some of the strategies to be considered.

6. Conclusion

The current study deals with high temperature proton exchange membrane fuel cells and its utilization for residential applications. Most specifically, the study being carried on deals with the system control to optimise both efficiency and lifetime expectancy of the mentioned fuel cells.

In future research to be presented, adequate control algorithms will be described and applied to a concrete mathematical model of the fuel cell. A similar procedure will be applied to a full CHP system (including compressor, heat exchanger and electrical power conditioning systems) focusing on comfort applications, that means, residential applications. The final step to be done will be checking these control algorithms in a real fuel cell system under laboratory conditions.

Acknowledgements

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