Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Power Sources 156 (2006) 64–70
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Study of a small heat and power PEM fuel cell system generator

Charles-Emile Hubert*, Patrick Achard, Rudolf Metkemeijer

CEP, Ecole des Mines de Paris, Sophia Antipolis, France

Available online 2 November 2005

Abstract

A micro-cogenerator based on a natural gas reformer and a PEMFC is studied in its entirety, pointing out the links between different sub-systems. The study is conducted within the EPACOP project, which aims at testing PEMFC systems on user sites to evaluate development and acceptance of this technology for small stationary applications. Five units were installed from November 2002 to May 2003 and have been operated until now, in real life conditions. They deliver up to 4 kW of AC power and about 6 kW of heat.

Center for Energy and Processes (CEP), one of the scientific partners, processes and analyses the experimental data from the five units, running in different regions of France. This database and the study of the flowsheet enable to propose changes to enhance the efficiency of the system composed of a steam reforming, a shift and a preferential oxidation reactor, a fuel cell stack and heat exchangers. The steady state modelling and optimisation of the system is done with Thermoptim®, a software developed within CEP for applied thermodynamics.

At constant power, main targets are to decrease natural gas consumption, to increase heat recovery and to improve the water balance. This study is made using the pinch point analysis, at full load and partial load.

Main results of this study are different system configurations that allow improvement of gross electrical and thermal efficiency and enable to obtain a positive water balance.

Keywords: Cogeneration of heat and power; Fuel processor; Fuel cell system; Modelling; Natural gas; PEMFC

1. Introduction

Small cogeneration PEMFC systems are gaining interest among power facilities and governmental organisations, especially in Japan and North America. In Europe, domestic gas and electricity suppliers, but also boiler manufacturers, are testing, adapting and trying to improve these devices in order to assess their ability to stick to efficiency, reliability and cost targets that meet European electricity market needs. These systems are fed with natural gas (NG) and deliver 1–10 kW of AC low voltage (LV) power and they are usually connected to a LV grid. Standalone systems are fed with propane.

This study is conducted in Center for Energy and Processes (CEP), in the frame of a French research project, named EPACOP,[1] led by Gaz de France, co-funded by ADEME, with collaboration of three CNRS laboratories in Nancy: LEMTA, GREEN and LSGC.

CEP has a 10 year experience in PEMFC stacks evaluation and PEMFC systems analysis. Since the development of its fuel cell test bench, it has worked on several French projects (CARBUPAC and SAPAREF) and European projects (FEVER, PMFP and PVFCSYS).

1.1. State of the art of NG-fed systems: what is a small cogeneration PEMFC system made of?

The system studied is mainly composed of a fuel processor, a stack and an electric compartment that contains converters, possibly batteries and the operation control system. These three sub-systems are usually put in three different compartments. As seen in Fig. 1, a fourth sub-system, commonly called "heat recovery sub-system" or "thermal management sub-system" links the two first sub-systems. It is not an additional compartment because water-cooling circuits and heat exchangers are deeply overlapped with fuel processor and stack sub-systems.

The zoom shows the fuel processor, which is most often made of a reforming reactor, one or two water shift reactors (shift) and a preferential oxidation reactor (Prox).

For stationary applications, the reforming reactor is a steam reforming reactor (SRR) or an autothermal reformer (ATR).

* Corresponding author.
E-mail address: charles-emile.hubert@ensmp.fr (C.-E. Hubert).

[1] Acronym of "Expérimentation de Piles À Combustible de petite taille sur sites Opérationnels" (testing small fuel cells on customer sites).

0378-7753/$ – see front matter
doi:10.1016/j.jpowsour.2005.08.022

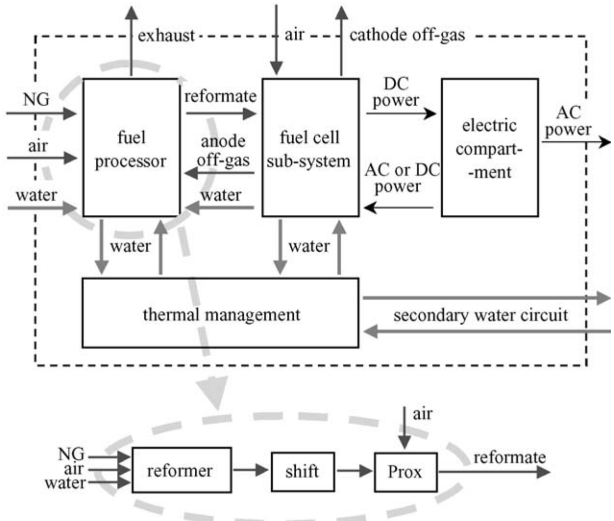

Fig. 1. Functional diagram of a small NG-fed cogeneration PEMFC system.

According to Refs. [1,2], SRR is often preferred to ATR for stationary applications because of a higher efficiency. It is effectively the case of main Japanese manufacturers (Osaka Gas, Tokyo Gas, IHI) who chose this technology. Nevertheless, Plug Power's GenSys™, which has been widely sold in the USA and among the world (with adaptation), produces hydrogen from natural gas using ATR.

The two technologies are mature and have rather close efficiencies. Many definitions of fuel processor efficiency are found in literature, this can be misleading. The definition chosen here is the one of Refs. [2,3], i.e. the ratio of lower heating value (LHV) of H_2 consumed in the stack to the LHV of total inlet NG. With a SRR-based fuel processor, the efficiency varies from 60% [4] to 78% [3] at full load.

The main difference between SRR and ATR is the concentration of hydrogen in dry reformate out of the Prox, 70–80% with SRR [5] and 30–46% with ATR [5,6]. It leads to different maximum utilisation rates of the anode gas. Because of a sharp increase of the anodic contribution of cell activation overvoltage when there is a lack of hydrogen near the membrane, a stack fed with reformate cannot use H_2 at 100%. The more the reformate rich in hydrogen is, the higher the utilisation rate can be. As it can reach 100% with pure hydrogen, 80–85% with reformate from SRR, it seems that it is not higher than 70% with a reformate from ATR [7].

This paper deals with steam reforming only.

A SRR is made of a (usually) tubular catalyst bed, where a mix of steam and NG ("feed mix") produces mainly hydrogen, carbon monoxide and dioxide and a burner where combustion of NG ("NG fuel") and anode off-gas brings heat to support the endothermic reaction in the bed. Exhaust gas is cooled warming-up the feed mix to temperature of reaction (600–900 °C) and boiling water.

The fuel cell sub-system is composed of a stack and its auxiliary equipment. The stack is typically made of 20–150 cells with an active area of 100–1000 cm^2 per cell. It delivers 2–10 kW DC. It is operated at low pressure (less than 200 mbar g) and at a temperature between 50 and 75 °C [8]. The main auxiliary in terms of power consumption is the air compressor. Then, a device to humidify and preheat this inlet air is necessary. Humidification of anode inlet gas may not be necessary because the reformate out of the Prox has a relative humidity between 60 and 100%.

At full load, the whole system has an electrical gross efficiency of 27% [4] to about 35%. Gross efficiency is the ratio of DC power produced by the stack to the LHV of total inlet NG. It is the product of the fuel processor and the PEMFC stack efficiencies. The energetic efficiency of the stack is defined as the ratio of the electric power produced to the LHV of consumed H_2. It depends on the conception (membrane electrode assembly, design of flow field channels, etc.) and operating conditions (temperature, pressure, humidity and utilisation rate).

Thermal efficiency of the system is defined as the ratio of the heat captured in the secondary water circuit to the LHV of the inlet NG, and has a value between 30 and 60%. A global efficiency can be defined as the sum of electrical and thermal efficiencies.

The fuel processor and the fuel cell sub-systems interact strongly, not only in the direction from fuel processor to fuel cell, but also in the other way, like anode off-gas (sent to the SRR burner), water produced by the cells (sent to the reaction chamber of SRR) and cooling circuit which crosses the two sub-systems (Fig. 1).

The fuel processor consumes water, while the fuel cell produces some. Water balance is the difference between collected water by condensation and needs of water for the fuel processing. It can be positive if enough liquid water is recovered, or negative if not. In the last case, additional water has to be brought to the system.

Once the design of the process is set, key parameters which characterize operating conditions are defined: "NG fuel" to total NG ratio (NG fuel/NG), steam to carbon ratio (S/C), air factor at the burner (λ), oxygen to carbon monoxide ratio at the inlet of Prox (O_2/CO), hydrogen utilisation rate in the anode (τ_{H_2}) and oxygen utilisation rate in cathode (τ_{O_2}).

$$\frac{\text{NG fuel}}{\text{NG}} = \frac{F_{\text{NG fuel}}}{F_{\text{NG total}}} \tag{1}$$

$$\frac{S}{C} = \frac{F_{H_2O}^{\text{SRR in}}}{\sum_i i F_{C_iH_{2i+i}}^{\text{feed}}} \tag{2}$$

$$\lambda = \frac{F_{O_2}^{\text{burner}}}{F_{O_2}^{\text{stoichio burner}}} \tag{3}$$

$$\frac{O_2}{CO} = \frac{F_{O_2}^{\text{PROX in}}}{F_{CO}^{\text{PROX in}}} \tag{4}$$

$$\tau_{H_2} = \frac{IN_{\text{cell}}}{[2FF_{H_2}^{\text{anode in}}]} \tag{5}$$

$$\tau_{O_2} = \frac{IN_{\text{cell}}}{[4FF_{O_2}^{\text{cathodein}}]} \tag{6}$$