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Short communication

Experimental results with a natural gas cogeneration system using a polymer exchange membrane fuel cell

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Abstract

This paper reports experimental results of an investigation of five identical CHP (combined heat and power) units using PEMFC (proton exchange membrane fuel cell) and running on natural gas. The natural gas is reformed locally to produce hydrogen. The net electric power is 4.5 kWe and the installations are designed for low temperature heat recovery (6 kW at 60 °C). The performances of the CHP units are analyzed in terms of electrical, thermal and total efficiencies. The electrical efficiency is low and it is shown that this is due mostly to the reforming process and to electric losses, while fuel cell performances are fully satisfying.

Keywords: PEMFC; Fuel cell; Experimental results; Electrical efficiency; Thermal efficiency; Total efficiency; Cogeneration; Natural gas reforming

1. Introduction

The results we present refer to an electrical power system of 4.5 kWe, using PEMFC (proton exchange membrane fuel cell), running on natural gas and adapted to low temperature heat recovery (6 kW at 60 °C). It is designed and built by H-Power (RCU 4500 V2). Five identical units were put in operation in France between November 2002 and June 2003. The cities participating to these experiments in real operating conditions are Dunkerque (2 units), Nancy, Limoges and Sophia-Antipolis. This work was carried out within the framework of EPACOP project, led by *Gaz de France* and co-funded by the French agency for energy and environment (ADEME).

One of the most important characteristics of PEM fuel cells is their low operating temperature (50–80 °C), which is a drawback for efficient heat recovery [1].

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2. System description and operation

Lombard et al. [2] published a detailed experimental analysis of the steam reforming unit (Fig. 1). The steam reforming and water–gas shift reactions occur at 650 °C in the reformer. Steam is fed in excess in order to inhibit amorphous coke formation [3]. The steam to carbon ratio *S*/*C* is between 6.5 and 8.1 [2], which is higher than the usual *S*/*C* ratio of natural gas conversion units for fuel cell applications [4]. Consequently, the water concentration of the outlet gas is high: between 0.35 and 0.55 mol_{H_2O}/mol_{gas} [2,5].

The cooler-shift eliminates by oxidation most of the carbon monoxide remaining in the reformer outlet gas. Although depending on the gas mixture flow rate, the conversion of carbon monoxide is good: 99.4% at $I = 40$ A and 98.6% at $I = 80$ A [2]. The gas is also cooled in two stages: first, high temperature heat (190–220 °C) is recovered by the steam; second, the cogeneration water further cools the gas through a heat exchanger located in the bottom part of the cooler-shift.

The prox is a catalytic reactor that eliminates the remaining carbon monoxide by preferential oxidation in the presence of a

Nomenclature

E	fuel cell potential (V)
F	Faraday constant $F = 96485\,\mathrm{C\,mol^{-1}}$
$\bar{g}$	Gibbs free energy ($\mathrm{J\,mol^{-1}}$)
$\bar{h}$	enthalpy ($\mathrm{J\,mol^{-1}}$)
I	current intensity (A)
N	number of cells in the fuel cell stack (–)
$\dot{n}$	molar flow rate ($\mathrm{mol\,s^{-1}}$)
$\dot{Q}$	thermal power of the system (kW)
T_{FC}	fuel cell temperature (°C)
$\dot{W}_e^{gross/net}$	gross/net electric power of the system (kW)
x	maximum number of hydrogen moles produced by mole of natural gas
η	efficiency (–)
λ_{NG}	coefficient of excess of reformed natural gas: $\lambda_{NG} = \frac{\dot{n}_{NG}^{ref}}{\dot{n}_{NG}^{min}}$ (–)

Subscripts and superscripts

br	burned
comb	combustion
e	electrical
FC	fuel cell
NG	natural gas
ref	reformed
th	thermal

small amount of air. The prox intake airflow is constant (470 *l*/*h*). Part of the oxygen reacts with carbon monoxide and the rest reacts with hydrogen. The amount of hydrogen consumed in the prox depends on the reformate flow rate (4.8% at $I = 40$ A and 3.1% at $I = 80$ A, [2]).

The fuel cell stack is made of $N = 120$ cells. Anode off-gas is injected into the reformer burner where excess hydrogen and the small amount of remaining methane are burned. An enthalpy wheel is used to recover water and heat from cathode outlet airflow and to transfer them to the cold and dry inlet airflow.

The primary water-cooling circuit goes successively through the shift, prox, and fuel cell. Then, heat is transferred to the user's circuit through another heat exchanger (not represented in Fig. 1). The maximum water temperature in the user's circuit is between 57 and 59 °C. If the demand is insufficient, heat is evacuated to the outside.

The units have an hybrid architecture: both fuel cell and batteries provide electricity. They integrate three electric converters: a DC/DC converter for raising the stack potential and making possible batteries charging, a DC/AC converter (60 Hz) for supplying the auxiliaries, and another DC/AC converter (50 Hz) for the main supply.

3. System efficiencies

3.1. Theoretical maximum electrical efficiencies

The maximum electrical efficiency of a fuel cell consuming hydrogen is given by (1)

$$\eta_{FC,H_2}^{max} = \frac{\Delta \bar{g}_{H_2,comb}}{\Delta \bar{h}_{H_2,comb}} \quad (1)$$

where $\Delta\bar{h}$ and $\Delta\bar{g}$ are the enthalpy and the Gibbs free energy of the overall reaction. The value of this ratio depends on temperature and activity of the reactants (H_2 and O_2) and of the product (H_2O): in the particular case of a PEMFC fed by hydrogen and air and operating at 60 °C, the theoretical maximum electrical efficiency equals 79% (since the cogeneration system recovers part of the latent heat of condensation of water, the HHV is used

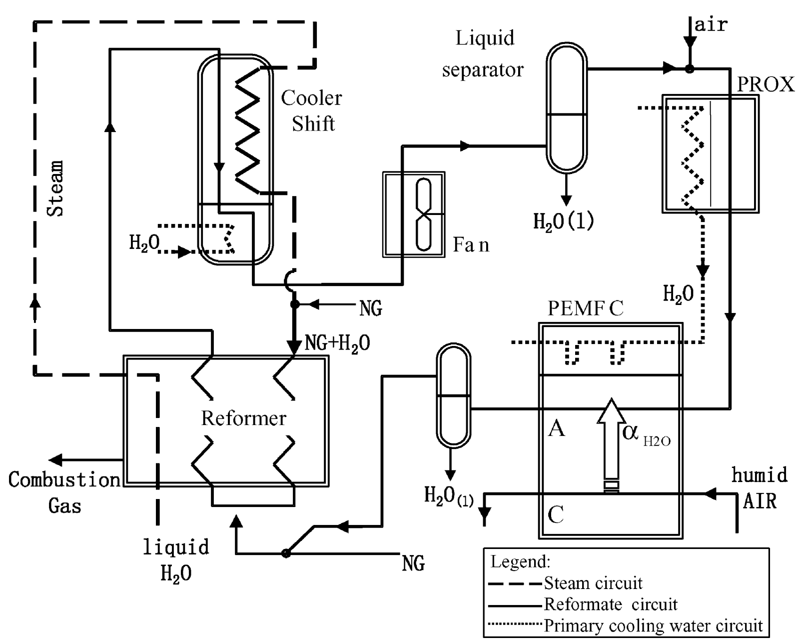

Fig. 1. System main components.