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An assessment of the energetic flows in a commercial PEM fuel-cell system

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ABSTRACT

Some primary issues have not yet been fully investigated on the way towards the commercialization of fuel-cell-based systems (FCS), e.g., their actual efficiency, reliability, safety, degradation, maintainability, etc. This article deals with an estimation of the real energetic flows and the corresponding electrical efficiency of a commercial proton-exchange-membrane fuel-cell hydrogen-fed generator set (PEMFCS). The fuel-cell power system considered here is planned to be the source of both electrical and thermal energy in a mobile dwelling container unit with in-built fuel-cell-based cogeneration system, and for the design of a cogeneration unit the actual amount of disposable energy from the PEMFC unit should be estimated. The assessment of the actual energetic flows, the disposable energy and the consequent electrical efficiency of the case-study PEMFCS is carried out using commercial technical data for the PEMFCS.

1. Introduction

Global climate-warming issues accompanied by the economic and strategic issues associated with fossil fuels are strong motivations to finding and developing replacement technologies for the supply of energy. One of the emerging alternatives being considered is a gradual change to a hydrogen economy, where hydrogen would become the primary energy carrier. Hydrogen is a suitable fuel for the efficient transformation of the chemical energy in the hydrogen into electrical, thermal or mechanical energy. The use of fuel-cell-based systems (FCS) provides considerable benefits compared to conventional internal combustion engines, mainly in terms of higher efficiency, quiet operation and very low emissions of pollutants. The hydrogen-fuelled proton-exchange-membrane fuel-cell system technology considered here is one of the most realistic and viable fuel-cell options currently available.

A literature review covering the past 10 years clearly demonstrates the amount of research-and-development work focused on the narrow domain of PEMFCS and hydrogen-related technologies [1–5]. However, the basic research activities on fuel cells have reached the stage of maturity, which means important progress towards the commercialization and industrialization of the FCS as an alternative generator of electrical and heat power in various power systems, industrial, transportation, domestic applications and other areas of human life is expected in the future.

We are engaged in the development of a mobile dwelling container unit (for up to three persons) with in-built fuel-cells-based cogeneration system, where a commercial PEMFCS [6] is used for the supply of electrical and heat power. The choice of the PEM type of cell for the FCS for cogeneration is unusual, but because of the type of application (i.e., military), the availability and some other properties of this type of fuel cell (i.e., silent operation, low temperature footprint, etc.) the PEM type prevailed.

The objective of the article is twofold: (a) to make an assessment of the electrical and heat energetic flows in the commercial PEMFCS for further exploitation of the produced heat in the thermal part of a cogeneration system and (b) to estimate the actual electrical efficiency of a fully loaded PEMFCS considered. The assessment of the actual energetic flows, the disposable energy and the consequent efficiency of the case-study PEMFCS was carried out using the technical data of a commercial PEMFCS. In this way we wanted to get an insight into the real energetic flows in the PEMFCS considered and to clarify the reasons for the various undesired electrical and thermal losses inside the system.

2. The PEMFCS considered

The PEMFCS considered in this analysis [6,7] has an output of 7000 W DC, with the power delivered through a DC/DC converter and a battery. The stack FC1 operates at a maximum current of 150 A, a voltage of 55–75 V, and consists of 79 cells with an area of 200 cm^2 (each). The anode's hydrogen feed line starts with a supply from a pressurized cylinder (150 bar); this is followed by a two-stage pressure reduction (PRV 8, PRV 9) and stoichiometry

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Nomenclature

Symbol	Description
FCS	fuel-cell-based system
PEMFCS	proton-exchange-membrane fuel-cell system
HV	heating value of the hydrogen
LHV	hydrogen's lower heating value, $LHV = 120{,}970\ \mathrm{J\,g^{-1}}$
HHV	hydrogen's higher heating value, $HHV = 141{,}900\ \mathrm{J\,g^{-1}}$
p_{cell}	power of a single fuel cell (W)
ϕ_{cell_H2}	hydrogen flow rate of a single fuel cell ($\mathrm{g\,s^{-1}}$)
M, $M(H_2)$	hydrogen molecular weight ($M(H_2) = 2.016\ \mathrm{g\,mol^{-1}}$)
$M(H_2O)$	water molecular weight ($M(H_2O) = 18.015\ \mathrm{g\,mol^{-1}}$)
I	electrical current (A)
n	number of electrons
F	Faraday's constant ($F = 96{,}485\ \mathrm{A\,s\,mol^{-1}}$)
U	voltage of a single fuel cell (V)
η_{cell}	theoretical electrical efficiency of a single fuel cell
η_{cell_1}	fuel-cell electrical efficiency
η_{stack}	electrical efficiency of the fuel-cell stack
η_{PEMFCS}	actual overall system electrical efficiency of PEMFCS
P_{stack}	power of the fuel-cell stack (W)
P_{loss}	cumulative losses of PEMPCS due to parasitic loads
ϕ_{cell_loss}	losses of hydrogen in a single fuel cell ($\mathrm{g\,s^{-1}}$)
ϕ_{stack_H2}	theoretical flow rate of hydrogen in the fuel-cell stack ($\mathrm{g\,s^{-1}}$)
ϕ_{stack_loss}	flow of the actual hydrogen losses ($\mathrm{g\,s^{-1}}$)
$\phi_{exhaust}$	cathode exhaust volume flow ($\mathrm{S\,m^3\,min^{-1}}$)
ϕ_{H2O}	water produced in the reaction ($\mathrm{cm^3\,min^{-1}}$)
ϕ_{H2_vol}	hydrogen flow in $\mathrm{Sl\,min^{-1}}$ (standard litres/min)
ρ_{H2}	hydrogen density with standard conditions ($\rho_{H2} = 0.08988\ \mathrm{g\,l^{-1}}$)
N	number of fuel cells in a stack
R	universal gas constant ($R = 8.314\ \mathrm{J\,K^{-1}\,mol^{-1}}$)
J	theoretical thermal flow (W)
J_{vapour}	thermal flow of exhaust water vapour (W)
$J_{convect}$	total convection/radiation losses of the stack and pipelines (W)
c_p	specific heating value of water ($4.184\ \mathrm{J\,g^{-1}\,K^{-1}}$at 20 °C)
q_{evap}	specific evaporation constant of water ($2400\ \mathrm{J\,g^{-1}}$ at 45 °C)
ρ_{vapour}	vapour density of water ($\mathrm{g\,l^{-1}}$)

regulation (pressure regulation valve PRV 13), pressure switches (PSL 11, PSH 15,), and pressure safety valves (PSV 6, PSV 7). Finally, it ends with a dead-end loop, a recirculation pump PMP 16 and a solenoid purge valve SV 17. The cathode's air-supply stream starts with a dust filter FLT 18; this is followed by a flow measurement FT 19, a motor-driven blower BLR 21, and a humidification unit SAT 22 (internal rotation type). The stack's cathode exhaust outlet and the original cooling unit FAHX 26 (a forced water/air heat exchanger) have a conventional layout and are set to operate at a maximum of 60 °C. The control system implements a number of regulation loops, as well as controlling the operation within the safe envelope of the process parameters. The corresponding basic process and the instrumentation diagram are shown in Fig. 1.

The commercial PEMFCS in our application is used as a generator set for both electrical and thermal energy installed in a mobile container. For this reason the original cooling unit FAHX 26 was removed. The flow of hot water from the stack as a source of heat energy is now redirected to the thermal part of the cogeneration unit.

3. Qualitative review of energy flows

The amount of energy that is contained in a fuel (in our case hydrogen) is defined either by the lower heating value *LHV* or the higher heating value *HHV*. Both values are defined as the ratio between the energy released during fuel burning and the fuel mass; the difference is in the measuring procedure. The lower heating value of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 150 °C. By contrast, the higher heating value (*HHV*) includes the heat of condensation of the water in the combustion products. The difference between both values depends on the amount of hydrogen in the fuel. Namely, the product of burning the hydrogen is water, which during its cooling from 150 °C to 25 °C releases, due to condensation, a significant amount of heat (the hydrogen's higher heating value is $HHV = 141{,}900\ \mathrm{J\,g^{-1}}$, the lower heating value $LHV = 120{,}970\ \mathrm{J\,g^{-1}}$).

The hydrogen fed into the PEMFCS is the carrier of the bounded chemical energy, which in the PEMFCS is transformed into electrical energy and heat. When the PEMFCS operates in a laboratory with a temperature around 25 °C, and the heat produced increases the internal energy of the laboratory, the sum of the electrical and heat energy produced roughly corresponds to the higher heating value of the hydrogen being consumed.

A closer look at the functioning of the PEMFCS shows us that things are not as simple as they seem to be. Because during the operation of a real PEMFCS not all of the hydrogen conveyed can react in the system, a part of it is released into the atmosphere. The majority of the heat generated as a by-product of the electrochemical reactions in the stack is taken away by the cooling subsystem and can be used for further exploitation. The total energy released is a little smaller than the hydrogen's higher heating value as the temperature of the products is above 25 °C. Nevertheless, the total energy released is much closer to *HHV* than *LHV*; i.e., the majority of the produced water is liquefied. A part of the heat is carried off by the cathode air, which has a higher temperature than at the input, and part of the heat is lost by convection and radiation to the surroundings. Also, a part of electrical energy produced in the stack is used in different sub-systems, where most of it is transformed into heat, which is then also lost to the surroundings. The rest of the electrical energy (7 kW [6]) is available for use. A more realistic overview of the energetic flows inside the PEMFCS is shown in Fig. 2.

4. Quantitative calculations of the energy flows

4.1. Hydrogen consumption

In 10 h the fully loaded PEMFCS considered here consumes 54,000 Sl (standard litres) of hydrogen, which gives a rate of $\phi_{H2\_vol} = 90\ \mathrm{Sl\,min^{-1}}$ [6]. The density of hydrogen in standard conditions is $\rho_{H2} = 0.08988\ \mathrm{g\,l^{-1}}$. Hence, the mass flow of hydrogen is equal to

$$\phi_{mass} = \rho_{H_2} \cdot \phi_{H_2\_vol} = 0.08988 \cdot 1.5 = 0.13482\ \mathrm{gs^{-1}}. \qquad (1)$$

The maximum electrical current in the PEMFCS considered is limited to 150 A, where the stack is composed of 79 serially connected fuel cells. According to Faraday's law of electrolysis, the amount of hydrogen that reacts in the stack is

$$\phi_{stack\_H_2} = \frac{N \cdot I \cdot M}{n \cdot F} = \frac{79 \cdot 150 \cdot 2.016}{2 \cdot 96{,}485} = 0.12379\ \mathrm{gs^{-1}}. \qquad (2)$$

where N is the number of fuel cells in the series.