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Evaluation of an alkaline fuel cell system as a micro-CHP

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ABSTRACT

Micro-cogeneration is an emerging technology to reduce the non-renewable energy demand in buildings and reduce peak load in the grid. Fuel cell based cogeneration (CHP) has interesting prospects for building applications, even at relatively low heat demand. This is due to their partial load behavior which is completely different, compared to other micro-CHP technologies. Within the fuel cell technologies suitable for small scale CHP or micro-CHP, the existing configuration of an alkaline fuel cell system is analyzed. This analysis is based on validated models and offers a control strategy to optimize both water management and energy performance of the alkaline fuel cell system. Finally, the model of the alkaline fuel cell system with optimized control strategy is used to compare its part load behavior to other micro-CHP technologies.

1. Introduction

Micro-cogeneration (micro-CHP) for building applications is getting more attention [1–4]. Depending on size, several technologies are available. The most mature technologies are combustion based technologies, like micro-turbines, internal combustion engines [5] and Stirling engines [6–8]. For small sizes, they have a relatively low power-to-heat ratio. This makes them suitable for buildings with a relatively high heat demand. For the existing building stock they can be an alternative solution to boiler driven heating systems. However, due to an improved insulation rate and an increasing number of electric appliances [9–11] in buildings, the energy profile in buildings is changing [12,13]. To meet these future demands in buildings, technologies are preferred, promising higher power-to-heat ratios even at small scale.

In this prospect, fuel cell based micro-CHPs are a promising alternative in buildings with a relatively low heat demand. Fuel cells have the potential for high electrical efficiencies, compared to other technologies [14]. Contrary to other types of CHP-technologies, their electrical efficiency is independent of size. Moreover the electrical efficiency even increases at part load. The application of fuel cell technology as micro-CHP refocused the research and development efforts on fuel cells [15]. Next to stack performance and lifetime, the ability of heat recovery in the system design became an important research topic for possible improvements [15–17].

Different types of fuel cell technology are suitable as micro-CHP for building applications [18]. Solide oxide fuel cell (SOFC) technology is the most mature technology as it can run on natural gas [19]. Within buildings SOFC show to be already competitive with fuel oil and electrical heating systems. The viability could be increased by improving utilization of waste heat [17]. Next to SOFC, also micro-CHP systems based on proton exchange membrane fuel cells (PEMFC) are developing rapidly [19–21]. The energetic-exergetic comparison in [22] showed that PEMFC based systems use their fuel energy input more efficiently than SOFC based systems for building application. This was expected, since building applications do not require the high temperature of the SOFC system. Like PEMFCs, alkaline fuel cells (AFCs) work at relatively low temperature, in the range of 50–90 °C.

In Refs. [23,24,18] it is shown that within the domain of (micro-) CHPs for building applications, also an AFC-based system offers possibilities. Next to this, AFCs have the possibility to be manufactured at less cost, using non-noble materials [25]. Despite a diminished interest in the last decade in alkaline fuel cells, compared to PEMFC, the electrical efficiencies presented in Refs. [24,26] are still competitive to PEMFC and SOFC used for micro-CHP [27] and certainly to other CHP-technologies [1,2,4,5]. Recent studies show that efficiency improvements are still possible by using different preparation methods for the development of electrodes [25].

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Nomenclature

C	heat capacity (W/K)	$_C$	cold
P	power (W)	$_H$	hot
Q	heat (W)	$_{HE}$	heat exchanger
T	temperature (°C)	$_{KOH}$	electrolyte flow
c	specific heat capacity (J/kg · K)	$_{air}$	air flow
h	specific enthalpy (J/kg)	$_{aux}$	auxiliary equipment
$\dot{m}$	mass flow rate (kg/s)	$_e$	electrical
$\alpha_{partial}$	partial efficiency (%)	$_{fan}$	fan
Δ	difference (-)	$_{inverter}$	inverter
ϵ	effectiveness (-)	$_{mech}$	mechanical
η	efficiency (-)	$_{misc}$	miscellaneous
κ	model parameter (a.u.)	$_{pump}$	pump
		$_{ref}$	reference
Subscripts and acronyms		$_s$	saturated vapor
AFC	alkaline fuel cell	$_{surr}$	surroundings
CHP	combined heat and power	$_{system}$	system
FC	fuel cell	$_w$	water

1.1. Scope

As AFC-technology has some promising evolutions, an analysis on a system level is necessary to gain more insight in its technical potential as a micro-CHP.

Hence, an existing system set-up is evaluated, considering the influence of the external heating circuit and load variation on system performance. In this way the results can be put in perspective in comparison with other technologies for micro-CHP.

The paper provides a simulation based analysis of the system set-up and possible control strategies in order to maintain water management and optimize energetic performance.

2. Methodology

In previous work a stack model is developed and validated [28,29] to analyze the water management [29] and performance [30] of an alkaline fuel cell stack. The goal of our research is to evaluate the potential of a complete CHP-system based on AFC technology. Therefore, the stack-model developed in Refs. [28,29] is integrated in a complete CHP-system model. This will enable a simulation based comparison with other micro-CHP technologies.

Next to energetic performance, also safety and water management are important criteria. In Ref. [23] the safety is discussed of the present set-up. This work focuses on water management and energetic performance.

2.1. Water management

An important evaluation criterion for a fuel cell system is the effectiveness of the water management. This implies energy friendly solutions to remove excess water in the electrolyte flow or to prevent net evaporation of the electrolyte.

Next to this, the robustness of the settings for nominal operation will be investigated. A robust or steady operation implies that small parameter changes result only in small net production or evaporation of water in the electrolyte flow. This will limit the range of steady operation of the fuel cell. The thermal response of the system is relatively slow, which can be deduced from the measurements on the water level in Ref. [29]: a response time of 10–20 min of the water management on a new set-point is noticed. Therefore, a robust working point, regarding water management, is defined as a working point where the net water production or evaporation is kept lower than 0.2 ml/s, which corresponds to the contents of a glass of water every twenty minutes.

2.2. Performance

To evaluate the performance of a CHP-system and the effect of different operating and system parameters on the CHP-potential, the methodology used in [30] is repeated: the primary energy savings are calculated. These savings result from the comparison with a separate production of heat and electricity.

2.2.1. Efficiency of the CHP

To evaluate the CHP-potential of the fuel cell, the electrical and thermal efficiency are defined. These efficiencies are defined at higher heating value (HHV) as this facilitates comparing different fuel types and introducing necessary conversion factors.

- The electrical efficiency, α_e, is defined as the ratio of the net generated electric power, $P_{e,system}$, to the fuel input, $Q_{Fuel,system}$, Eq. (1). This efficiency, α_e, differs from the efficiency of the fuel cell stack itself, α_{FC}, which is discussed in [30] and defined by Eq. (2). This difference is found both in the definition of the fuel input as in the definition of the generated power. The fuel input of the system, $Q_{Fuel,system}$, includes the hydrogen, which is purged into the environment to remove water drops at the anode side and in the piping at the stack inlet. This is defined by a purge efficiency, η_{purge}, Eq. (3). The generated electric power (DC) by the fuel cell stack, $P_{e,FC}$, will be converted into AC power, $P_{e,AC}$, by the inverter at efficiency of the inverter, $\eta_{inverter}$, Eq. (4). The difference between the generated AC power, $P_{e,AC}$, and the net generated electric power, $P_{e,system}$, is found in the electric load of auxilary equipment, $P_{e,aux}$, Eq. (5). This load is the result of the electric energy needed for the electrolyte pump, $P_{e,KOHpump}$, fan power, $P_{e,airfan}$, monitoring and safety equipment, $P_{e,electronics}$, etc., $P_{e,misc}$, Eq. (6).

$$\alpha_e = \frac{P_{e,system}}{Q_{Fuel,system}} \tag{1}$$

$$\alpha_{FC} = \frac{P_{e,FC}}{Q_{Fuel,FC}} \tag{2}$$

$$\eta_{purge} = \frac{Q_{Fuel,FC}}{Q_{Fuel,system}} \tag{3}$$

$$P_{e,AC} = \eta_{inverter} \cdot P_{e,FC} \tag{4}$$