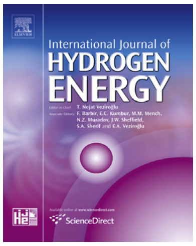
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 1569–1583

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



Mathematical modelling and parametric study on a 30 kW_{el} high temperature PEM fuel cell based residential micro cogeneration plant

Behzad Najafi[*], *Alireza Haghighat Mamaghani, Andrea Baricci,*
Fabio Rinaldi, Andrea Casalegno

Dipartimento di Energia, Politecnico di Milano, Via Lambruschini 4, 20156 Milano, Italy

ARTICLE INFO

Article history:
Received 16 August 2014
Received in revised form
16 November 2014
Accepted 17 November 2014
Available online 13 December 2014

Keywords:
Cogeneration
High temperature PEM fuel cell
Fuel processor
Parametric study
Residential system

ABSTRACT

A new configuration for an existing PEM fuel cell based residential micro-cogeneration system has been proposed in which the conventional low temperature PEM fuel cell is replaced with a high temperature one. Detailed mathematical models for the fuel processor, HT- PEM fuel cell stack and all other components of the plant have been developed. The electrical and thermal performance of the system have been determined and the corresponding results have been compared with the performance indices achieved for the previous plant. The electrical efficiency and the primary energy savings index obtained for the proposed system are 29.21% and 17.50% respectively which are considerably higher than the ones obtained for the existing LT-PEM based plant (21.18% and 6.07%). In order to enlighten our understanding of the behaviour of the system a parametric study on the key parameters of the system has been carried out.

Introduction

Proton exchange membrane (PEM) fuel cells have been widely recognized as efficient and zero emission power sources suited for stationary power generation and mobile applications. Amongst their numerous features, high power density, short start up due to low operating temperatures, high efficiency, long stack life, and noiseless operation make PEM fuel cells distinguished from the other types of fuel cells [1–5]. In addition, PEM fuel cells have a low thermal to electric ratio (TER) which provides them the superiority over combustion-based generation technologies for CHP applications at scales from 5 kW to 2 MW. Low temperature PEM (LT-PEM) fuel cells are the most common types of PEM fuel cells in which Nafion-based proton exchange membrane is employed and the operating temperature is around 80 °C. Several studies have been carried out so far on implementation of LT-PEM fuel cells for cogeneration and trigeneration purposes [6–9]. Ferguson et al. [10] developed a steady-state model of an LT-PEM fuel cell for building cogeneration applications and studied the effect of operating strategy and fuel cell sizing on the performance of the system. Radulescu et al. [11] performed an experimental and theoretical analysis on five identical CHP plants based on LT-PEM fuel cell installed in different cities in France. The employed system in their experiment could

---

[*] *Corresponding author*. Tel.: +39 02 2399 3840.
E-mail addresses: behzad.najafi@polimi.it (B. Najafi), alireza.haghighat@mail.polimi.it (A. Haghighat Mamaghani), andrea.baricci@polimi.it (A. Baricci), fabio.rinaldi@polimi.it (F. Rinaldi), andrea.casalegno@polimi.it (A. Casalegno).

http://dx.doi.org/10.1016/j.ijhydene.2014.11.093

Nomenclature

Acronyms

aux/proc	auxiliary to process flow rate ratio
CHP	combined heat and power
GDL	gas diffusion layer
HT-PEM	high temperature proton exchange membrane
LMTD	logarithmic mean temperature difference
LT-PEM	low temperature proton exchange membrane
MEA	membrane electrode assembly
OHM	ohmic
PBI	polybenzimidazole
PES	primary energy saving
PFSA	perfluorosulfonic acid
PrOX	preferential oxidation
RF	reforming factor
S/C	steam to carbon ratio
SMR	steam methane reforming
TER	thermal to electric ratio
WGS	water gas shift
WKO	water knock out

Symbols

E_{ID}	ideal voltage, V
E_a	activation energy, kJ mol^{-1}
f	friction factor
ΔH_{298K}	standard enthalpy of reaction, kJ $kmol^{-1}$
I	current, A
k	rate coefficient
K	equilibrium constant
LHV	low heating value, kJ kg^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
N	number of cells
Nu	Nusselt number
P_x	partial pressure of species x
P	power, kW
Pr	Prandtl number
$\dot{Q}$	the time rate of heat transfer, kW
r	rate of reaction, mol lit^{-1} s^{-1}
R	universal gas constant, kJ $kmol^{-1}$ K^{-1}
Re	Reynolds number
T	temperature, K
V	voltage, V

Subscripts

A	anode
C	cathode
cogen	cogeneration
el	electrical
th	thermal

Greek symbols

η_A	anodic voltage loss
η_C	cathodic voltage loss
η_{el}	electrical efficiency
η_I	first law efficiency
η_{th}	thermal efficiency
λ_{H_2}	anodic stoichiometric ratio

generate net electrical power of 5 kW and was equipped with a low temperature (e.g. around 60 °C) heat recovery system with 6 kW thermal output. Furthermore, Calise et al. [12] conducted a dynamic simulation of a polygeneration system based on solar collectors, absorption chiller and PEM fuel cells which is capable of providing electricity, space heating and cooling, and domestic hot water. In another study, steady state modelling and optimization of a small heat and power plant based on PEM fuel cell system was carried out [13]. In the optimization procedure conducted in this study, while keeping the power output constant, decreasing the natural gas consumption and increasing the heat recovery were considered as the objective functions.

Due to the importance of economic assessment in any newfound power generation system [14–17], some studies have taken into account the economic aspects of the PEM fuel cell based cogeneration systems. Contreras et al. [18] performed an energetic and economic study on the utilization of PEMFC based cogeneration systems in rural sector of Venezuela. Moreover, from the represented sensitivity analysis of electricity cost with time, a steady decrement of unit cost of electricity through time can be evidently seen which predicted the cost of 1$/kWh for 2020. Guizzi et al. [19] investigated the economic and energetic performance of a cogeneration system based on a PEM fuel cell fed by pure hydrogen produced in a membrane steam reformer. Besides the electrical power, the generated heat in the fuel cell and reformer was utilized to supply the needs of an office building, which finally resulted in net electrical and thermal efficiencies of 41.93% and 64.16% respectively at rated conditions. Roses et al. [20] compared the different membrane reactor configurations applied to a 2 kW micro-generation system based on an LT-PEM fuel cell. They underlined the key role of hydrogen production step in electrical and 2nd law efficiencies of the CHP system. In this regard, the adoption of membrane reactor technology (i.e. fixed bed and fluidized bed) resulted in overall electrical and 2nd law efficiencies of about 43% and 48% respectively, in comparison to 34% and 38% with conventional fuel processor.

Perfluorosulfonic acid (PFSA) polymer membranes specifically Nafion are the most widely used electrolytes in LT-PEM fuel cells owing to their elevated thermal and chemical stability, high ionic conductivity and electrical insulation [21,22]. Nevertheless, LT-PEM fuel cells with PFSA polymer membranes still have some shortcomings such as the slow kinetics of oxygen reduction, high material cost of noble catalysts, water management issues, and intensive required cooling [23,24]. In addition, the presence of carbon monoxide (CO) in reformate gas obtained by conventional fuel reforming methods adversely affects the LT-PEM performance due to the poisoning characteristic of CO for platinum anode catalyst. Accordingly, significant efforts have been made in order to mitigate or even evade all aforementioned obstacles on the way of efficient performance of the PEM fuel cells [25,26].

One of the well-known solutions to overcome the former issues, concerning the LT-PEMs, is the operation of PEM fuel cell at temperatures higher than 100 °C (high temperature PEM (HT-PEM) fuel cell). At high temperatures, the adsorption of