



A trigeneration system based on polymer electrolyte fuel cell and desiccant wheel – Part B: Overall system design and energy performance analysis



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ABSTRACT

This paper represents the second part of a major work focusing on a trigeneration system integrating a low temperature polymer electrolyte fuel cell (PEMFC) and a desiccant wheel-based air handling unit. Low temperature PEMFC systems have a significant potential in combined heating, cooling and power applications. However cogenerated heat temperature is relatively low (up to 65–70 °C), resulting in low efficiency of the cooling process, and the fuel processor is far from being flexible, hindering the operation of the system at low load conditions. Therefore a trigeneration system based on PEMFC should be carefully designed through accurate simulation tools.

In the current paper a detailed analysis of the energy performance of the trigenerative system is provided, taking into account constraints of real applications, such as PEMFC part load behavior, desiccant wheel effectiveness, heat storage losses and air handling unit electrical consumptions. The methodology adopted to model system components is deeply described. Energy simulations are performed on yearly basis with variable building air conditioning loads and climate conditions, in order to investigate the optimal trigenerative unit size. A sensitivity analysis on crucial design parameters is provided.

It is shown that constraints of actual applications have relevant effects on system energy consumption, which is significantly far from expected values based on a simplified analysis. Primary energy savings can be positive in winter time if the ratio of PEMFC heating capacity to air conditioning peak heating load is close to 0.15. Instead on yearly basis primary energy savings cannot be achieved with present components performance. Positive savings can be potentially achieved if PEMFC system and auxiliary devices are properly improved.

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1. Introduction

Combined heating, cooling and power unit based on fuel cells are of great interest due to potential increase in overall efficiency, reduction in primary energy consumption and near-zero emissions.

At present many research works deal with design and feasibility of trigenerative power plants. Kavvadias et al. [1], Balli et al. [2,3] and Zhao et al. [4] focused on trigenerative applications driven by internal combustion engines, Wang et al. [5] optimized an organic Rankine cycle-based CHCP system driven by solar energy while Al-Sulaiman et al. [6] compared electrical efficiency and cost rate of CHCP systems based on SOFC units, biomass and solar energy. Particular attention is given to small scale systems for

distributed units [7]; domestic scale trigeneration systems have a great potential but profitability [8] and performance of heat driven devices [9] are still key issues to cope with. Several research works deal with trigeneration based on fuel cells: Gabbar et al. [10] focused on a fuel cell system for energy conservation in a commercial building. The use of high temperature exhaust gas from SOFC has been widely discussed by Choudhury et al. [11]. Zink et al. [12] investigated the use of SOFC to provide heating, cooling and domestic hot water for buildings. Chen and Ni [13], Ranjbar et al. [14] and Fong and Lee [15] analyzed systems based on SOFC and absorption chiller, Al-Sulaiman et al. [16] evaluated energy performance of a system based on SOFC, organic Rankine cycle and absorption chiller and Tse et al. [17] investigated a SOFC hybrid trigenerative system for marine applications.

The use of PEMFC system is largely investigated in cogenerative arrangement such as households [18] or commercial greenhouses [19]. High temperature PEMFC for micro-cogeneration generally

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Nomenclature

Acronyms

CC	cooling coil
CR	capacity ratio
DEC	Desiccant Evaporative Cooling
DW	desiccant wheel
EC	Evaporative Cooler
EER	Energy Efficiency Ratio
F	Fan
HTHX	High Temperature Heat Exchanger
HTS	High Temperature heat Sink
HTT	High Temperature heat Tank
LTHX	Low Temperature Heat Exchanger
HTS	High Temperature heat Sink
HTT	High Temperature heat Tank
HW	heat wheel
MSBT	minimum stand-by time
PEC	Primary Energy Consumption
PEM	Polymer Electrolyte Membrane
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PES	primary energy saving
PLR	part load ratio
TPES	Trigeneration Primary Energy Saving

Symbols

C	cooling energy [MW h]
C_u	sensible and latent useful cooling energy [MW h]
$\dot{C}$	cooling capacity [kW]
F	fuel consumption [MW h]
$\dot{F}$	fuel consumption rate [kW]
Q	thermal energy [MW h]
Q_u	sensible and latent useful heating energy [MW h]
$\dot{Q}$	heating capacity [kW]
T	temperature [°C]
x	humidity ratio [g/kg]
U	overall heat transfer coefficient [W/m ² /K]
v	velocity [m/s]
V	volumetric flow rate [m ³ /h]
W	electrical energy [MW h]
W_u	useful electrical energy [MW h]
$\dot{W}$	electrical power [kW]

Subscripts

60%	at 60% of maximum load
100%	at full load
a	air
AHU	air handling unit
b	boiler
c	vapor compression chiller
el	electrical
ext	external
F	fan
HS	heat sinks
in	inlet
j	generic j component
$loss$	heat loss
LTS	low temperature heat sink
LTT	low temperature heat tank
max	maximum
min	minimum
out	outlet
P	pump
$peak$	peak load condition
ref	reference system
rb	reference building
SB	stand-by
ST	storage tanks
tri	trigenerative system
tot	total
w	water

Superscript

i	time step
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Greek letters

α	air conditioning loads scaling factor
ΔP	pressure drop
ΔW	difference in electrical energy consumption
η	efficiency

leads to higher primary energy saving due to a better electrical efficiency [20,21]. Only a small number of works deal with a trigenerative configuration integrating absorption chillers [22,23], mainly due to the low fuel cell operating temperature which limits the performance of the heat driven cooling process.

In case of trigenerative systems driven by a low temperature heat source ($T < 70$ °C), desiccant wheel-based dehumidification units integrated with vapor compression cooling devices represent a suitable technology [24]. Other thermally driven cooling devices, such as adsorption or absorption chillers, suffer from poor energy efficiency ratio, which is limited to 0.5 in the best working conditions [25,26]. On the other hand it is shown that desiccant wheel-based cooling can actually save primary energy compared to the reference technology, especially if coupled with cogenerators [24,27,28] or even gas heaters [29]; in addition, indoor air quality can benefit from sorption wheels [30]. However energy savings strongly depend on boundary conditions, such as air temperature and humidity, sensible and latent loads.

As reported in part A [41] of this work, low temperature PEMFC systems are quite a mature technology in terms of yearly operating hours and potential applications. In the present paper a trigenera-

tion system integrating a low temperature PEM fuel cell and a desiccant wheel based air handling unit is designed and analyzed. Technical constraints, specifications of real systems and actual performance of each device at full and part load are precisely taken into account. According to the foregoing literature review, such a system has not been investigated in spite of possible energy savings compared to the conventional technology.

Energy simulations are carried out for a trigenerative plant coupled with an office building and performance are assessed on yearly basis in terms of TPES (Trigeneration Primary Energy Saving) [31]. The optimal system configuration is identified and the effect of climate conditions is evaluated. Finally the effects of PEMFC system improvements are analyzed and the increase in the primary energy saving is evaluated.

2. Adopted performance index of the trigenerative system

In the present work TPES (Trigeneration Primary Energy Saving) index [31] is used to evaluate the potential benefits of the trigenerative system. According to Fig. 1, the control volumes include:

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