INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2016) 1–17

Available online at www.sciencedirect.com

ScienceDirect

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

PEM fuel cell heat recovery for preheating inlet air in standalone solar-hydrogen systems for telecommunication applications: An exergy analysis

Huy Quoc Nguyen [*], *Asma Mohamad Aris* [1], *Bahman Shabani* [2]

School of Engineering, RMIT University, Melbourne, Australia

ARTICLE INFO

Article history:
Received 22 September 2015
Received in revised form
15 December 2015
Accepted 17 December 2015
Available online xxx

Keywords:
PEM fuel cell
Exergy analysis
Exergetic efficiency
Fuel cell heat recovery
Telecommunication application
CHP

ABSTRACT

In this paper, a theoretical model of a PEMFC with heat recovery system (PEMFC-HR) for preheating its inlet air to mitigate the performance degradation, when the fuel cell operates in an extreme cold environment, is proposed and evaluated by using exergy analysis. In this modeling study, HOMER and TRNSYS software tools are used to simulate the yearly load profile of a PEMFC in the context of a standalone hybrid solar-hydrogen system (hybridized with batteries) for telecommunication application in cold climate conditions. A dynamic theoretical model of the PEMFC-HR is then built in MATLAB environment to simulate and investigate the impacts of input parameters on the performance of such system. Furthermore, by using a high effectiveness heat exchanger (HE), the inlet air temperature of the PEMFC can be increased from sub-zero to well above the freezing point temperature. The impacts of the various ambient temperatures and fuel cell power on the exergetic efficiency of PEMFC-HR are then theoretically investigated and compared with the PEMFC coupled with an external electric heater (PEMFC-EH). Based on a case study for Eureka, Canada, the modeling results showed that approximately equivalent to 30% of the electrical energy, generated annually by the PEMFC, can be saved by replacing the PEMFC-EH arrangement with a PEMFC-HR system.

* *Corresponding author*. Tel.: +61 04 5170 0686; fax: +61 03 9925 8099.
E-mail addresses: quochuybkdn@gmail.com (H.Q. Nguyen), asmamohamadaris@gmail.com (A.M. Aris), bahman.shabani@rmit.edu.au (B. Shabani).
[1] Tel.: +61 04 6875 9464.
[2] Tel.: +6103 9925 4353; fax: +61 03 9925 8099.

http://dx.doi.org/10.1016/j.ijhydene.2015.12.108
0360-3199/

Introduction

PEMFC operation in cold climate conditions

Proton Exchange Membrane Fuel Cells (PEMFCs) have proven to be a promising energy conversion technology (i.e. converting the chemical energy of hydrogen into electricity) in various automotive, stationary and portable power supply applications. The key advantages of deploying PEMFCs are their high power density, low operating temperature (e.g. 60–100 °C), quick start-up and fast response to variable loads [1–3]. For PEMFCs operating in extreme cold climate conditions, the water and thermal management of the stack are the key technical challenges that are constantly being addressed by many researchers and relevant industries [4,5]. This is because, during the operation of PEMFCs under sub-zero temperature conditions, the water generated as the result of electrochemical reaction between oxygen and hydrogen molecules in the cells, can be frozen and cause issues such as performance degradation, membrane dehydration, long-term durability impact, and slow start-up [5,6]. Furthermore, the internal structure and components of the PEMFC can be potentially damaged due to the mechanical stress caused by the expansion of ice formation and contraction of melting process [7]. Additionally, the ice formation that can potentially exists at the cathode and anode, as well as the flow channels and the pathways of gas diffusion layer, can prevent the movement of the reactants and their access to the reaction sites [6,8].

A wide range of studies can be found in the literature confirming that ice formation in PEMFCs operating under extreme cold conditions can lead to a significant degradation of the cell performance [9–12]. Cho et al. [12] studied the effect of freeze/thaw thermal cycles towards the performance of a PEMFC from −10 °C to 80 °C and found that the current density of the PEMFC decreases from 860 mA/cm^2 to 780 mA/cm^2 (i.e. ~10% drop) after four thermal cycles. The reasons being that are due to phase transformation and volume changes of water during shutdown and start-up operations [12]. Similarly, more than 5% performance degradation for each freeze/thaw cycle was found by Oszcipok et al. [9] and that a small degradation was observed by Alink et al. [11] when they investigated the mechanism of ice formation in the stack during freeze/thaw cycles.

The freezing temperature of inlet air coolant and reactants has a significant effect not only on the performance degradation of the PEM fuel cell, but also the success of maintaining the cell operated at certain power outputs. Chu et al. [10] reported on operating a PEMFC at −10 °C for about 9 h while freezing of water in reactants' supplying pipes resulted in a significant drop in the voltage of the PEMFC. Begot et al. [13] tested the effect of sub-zero temperatures (i.e. −5 °C, −10 °C and −15 °C) on the cold start and in-operation performance of a 2-kW PEMFC. The results showed that lower inlet air temperatures lead to shorter operating times of the cell and that the shortest operating time was found at the lowest tested temperature of −15 °C. Mukundan et al. [14] discussed that the water generated at the cathode of the cell tends to form ice during the cell's operation in the extreme cold climate condition where this causes a decline in the performance of the stack. Additionally, by utilizing neutron radiography, Mukundan, et al. [15] found that the ice formation mainly concentrated near the inlets, outlets and cell edges under the operation of the PEMFC at −10 °C. Yan et al. [6] experimentally investigated the effect of extreme ambient temperatures (−15 °C and 80 °C) on the performance of a 25 cm^2 PEMFC. The findings of this study showed that the performance of the fuel cell increased significantly from about 200 mV to around 500 mV cell voltage at 750 mA/cm^2 current density after the chamber's temperature increased from −15 °C to 25 °C. Additionally, the best performance of the fuel cell was recorded at 25 °C (Fig. 1a). Likewise, the temperatures of the cathode were measured against different ambient temperatures and air stoichiometry ratios. The results suggested that the cathode's temperature was stable at 25 °C, 0 °C, −5 °C, and −10 °C of ambient temperatures (Fig. 1b). Nevertheless, the instability of the cathode's temperature was experienced after four thermal cycles at −15 °C of chamber's temperature. In summary, previous studies have all underlined the importance of adopting effective strategies to increase the inlet air temperature of a PEMFC, when operating in cold climate condition, in order to improve its performance and durability.

PEMFC thermal management opportunities in cold climate conditions

Various strategies have been proposed for rapid cold start and mitigation of durability issues due to performance degradation of PEMFCs operating under extreme cold condition. Datta et al. [16] tested a 500 W PEMFC in Antarctic, where the ambient temperature was down to −40 °C. The research by Datta et al. suggested air cooling to be more feasible than water cooling in this condition; however, additional power was required for heating up the air coolant. Reiser [17] invented an auxiliary load and batteries to supply heat for PEMFC's cold start. An extended study by Reiser and Sribnik [18] suggested that a melted coolant can be used to heat up the coolant channels where the heat to melt the coolant is obtained from a heater that is powered by a battery. Korytnikov and Novak [19] proposed a PEMFC with a channel to fill the hydrogen into the cathode. The cathode catalyst could be heated up due to the chemical reaction between hydrogen and oxygen. Furthermore, Dewey [20] designed a heater that was integrated into a cold plate in order to warm up the coolant in the stack during start-up.

The heat generation within the PEMFC due to irreversibilities associated with electrochemical reactions and Ohmic loss, accounts for between ~40% and ~60% of the total reacted hydrogen energy content [21,22]. To prolong the lifetime and performance of the PEMFC, this heat has to be effectively removed from the stack by using a properly designed cooling system [23]. Considering this amount of heat that is normally wasted, the heat recovery from the PEMFC is an attractive idea due to opportunities to achieve higher overall energy efficiency for the fuel cell when operated to supply both heat and power – i.e. a combined heat power (CHP) system. Because the operating temperature range of a PEMFC is usually between 60 °C and 100 °C [23,24], the PEMFC-based CHP technology has been mainly researched and developed for small-scale low