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Study of a thermal bridging approach using heat pipes for simultaneous fuel cell cooling and metal hydride hydrogen discharge rate enhancement

Anggito P. Tetuko, Bahman Shabani*, Reza Omrani, Biddyut Paul, John Andrews

School of Engineering, RMIT University, Australia

HIGHLIGHTS

- Heat pipes were used for thermal coupling of a PEM fuel cell and MH canister.
- 20–30% of the fuel cell heat is enough to maintain the flow of MH H_2 storage.
- Fuel cell heat helps maintain the temperature of MH H_2 storage at above 25 °C.
- Heat pipes can be used practically for thermal management of PEM fuel cells.

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ABSTRACT

Low hydrogen discharge rate of Metal Hydride (MH) hydrogen canisters is a common challenge for this type of storage when used to supply hydrogen to Proton Exchange Membrane (PEM) fuel cells. The present paper investigates the use of fuel cell heat, transferred using heat pipes, to enhance the hydrogen release rate of MH canisters. Both the theoretical models and the experimental study on a 130-W PEM fuel cell supplied by an 800-sl MH canister (used as a case study), confirmed that ~30% of the fuel cell cooling load is sufficient to maintained the temperature of the canister at ~25 °C, required for the MH canister to supply hydrogen at 1.7 slpm (as demanded by the fuel cell for operation at 130 W). Using additional heat pipes (i.e. to remove the remaining ~70% the fuel cell cooling load), the temperature of the fuel cell could be maintained at ~60 °C. The study also confirmed that this thermal management system can deliver relatively uniform temperature distributions across the stack and the MH canister with less than 5 °C of temperature gradient across these components.

1. Introduction

Proton Exchange Membrane (PEM) fuel cells generate electricity through electrochemical reactions between hydrogen and oxygen molecules (usually from air) with water and heat as by-products [1–3]. PEM fuel cells have been receiving increasing attention globally for a wide range of stationary [4–7] and mobile applications [8–12]. They must operate within a certain range of temperature, normally at 60-80 °C [13,14], so that the heat generated by the fuel cell stack has to be continuously removed through a properly-designed cooling system. The heat collected from the stack can be utilised for some thermal applications (i.e. in combined heat and power arrangements) such as space heating [15,16], hot water supply [17–21], or even pre-heating of the reactants (before entering the stack) in cold climatic conditions [22,23].

This paper focuses on another promising application for the heat generated by a PEM fuel cell that is for increasing the temperature of Metal Hydride (MH) canisters used to supply hydrogen to the fuel cell. Heating up the MH canisters can enhance their hydrogen release rate and match the rate of hydrogen supply with that demanded by the PEM fuel cell, particularly at its maximum operating power [24–27]. The process of releasing hydrogen from the MH is an endothermic reaction for which heat has to be supplied to the MH in order to maintain its temperature at a required level (usually in the range of 20–30°C). The hydrogen release rate from MH storage systems is sometimes a challenge when it is cannot match the maximum rate demanded by the PEM fuel cell. The easiest and most common solutions are then using an external source of heat to increase the temperature of the MH storage tanks/canisters or increasing the size of the storage by adding extra canisters. Neither of these solutions is desirable: the first solution adds to the parasitic energy of the systems and the second solution obviously adds to the mass and space requirements of the overall system; and hence both solutions add to the running or capital costs of such hydrogen systems. On the other hand, by utilising the heat generated by

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* Corresponding author.
E-mail address: bahman.shabani@rmit.edu.au (B. Shabani).

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the PEM fuel cell to enhance the hydrogen release rate from the MH canisters, the need for adding extra canisters can be avoided [25,28–30].

Several researchers have explored the opportunities for thermal coupling between the PEM fuel cells and MH hydrogen storage systems. Wilson et al. [31], Jiang et al. [32] and Pfeifer et al. [33] all used active methods (e.g. liquid or air) with heat exchangers or heating baths to implement this idea. Obviously, one of the disadvantages of such active methods is the parasitic energy involved that decreases the overall energy efficiency of the fuel cell system. Moreover, the extra components required for active thermal management are always undesirable. On the other hand, heat pipes with high thermal conductivities (in the range of 1000-100 000 W/m.K) offer an opportunity for passive thermal coupling of PEM fuel cells and MH canisters. Heat pipes can usually remove a large amount of heat in a short time because of their high effective thermal conductivity, while offering the flexibility of being used in different orientations, which can be useful in applications with spatial limitations). Further advantages of heat pipes are their simplicity, low maintenance, and extended lifetime [34].

The idea of using heat pipes for thermal coupling of PEM fuel cells and MH hydrogen storage has been theoretically investigated by the authors under steady-state conditions earlier by using analytical modelling [35]. However, the model was never validated using a real fuel cell experimentally. Moreover, the model was not able to provide any information about the transient behaviour of this arrangement. In the present paper first the earlier analytical model [35] was applied to a case study of a PEM fuel cell supplying at maximum 130 W of electrical power, using hydrogen from an 800-sl MH canister, with these two components coupled thermally by custom-sized and designed heat pipes. The analytical investigation of this case was then complemented by a transient numerical analysis as well as an experimental investigation, in order to understand the transient behaviour of the system, the corresponding temperature distributions across the canister and the fuel cell stack, and last but not least the overall feasibility and practicality of the idea. Experimental data is presented and discussed while being used to demonstrate the validity of both the analytical and numerical simulation models.

A brief review of previous studies on thermal coupling of PEM fuel cells and MH canisters is provided in section 2, and the method used in the present study is described in section 3. Section 4 describes the theoretical modelling on the case study, followed by the details of the experimental study in section 5. In section 6, the results of both theoretical and experimental studies are presented, discussed, and compared. Conclusions are presented in section 7.

2. Thermal coupling of PEM fuel cells and MHs

A limited number of studies can be found in the literature covering thermal coupling of fuel cells and MH hydrogen storage systems, mainly focussing on active coupling arrangements.

The study conducted by Pfeifer et al. [33] is one of the earliest ones in the literature covering this topic. In this study, a 1-kW high-temperature PEM fuel cell (i.e. operating in the range of 160-200 °C) was thermally coupled with four MH canisters. The PEM fuel cell stack consisted of ten cells with membrane active area of 256 cm^2 in each cell, and each of the MH canisters was filled with 2 kg sodium alanate, capable of absorbing 36 g of hydrogen (i.e. total of 154 g could be stored in four canisters). While the amount of hydrogen stored in the canisters (i.e. 154 g) was enough to supply the fuel cell at its rated power for about 2.5 h of operation (as required for certain applications they had in mind), the maximum hydrogen supply rate of each canister (used in this study) was only about 2 slpm, or 8 slpm for four canisters (i.e. not enough to meet the demand of the stack at 1 kW). It is noteworthy, that normally a kW fuel cell demands about 9–12 slpm (depending on its hydrogen utilisation factor) at its rated power. Pfeifer et al. used an active thermal coupling arrangement between the stack and the canisters with oil used as the heat transfer medium to direct part of the fuel cell heat to the canisters. The study concluded that by transferring 150 W of the fuel cell cooling load (i.e. about 15% of the total cooling load of the stack) at 185 °C, the maximum hydrogen release rate form the MH canister could be enhanced by up to about 75%, enough to meet the fuel cell demand for hydrogen at its rated power (i.e. 1 kW). The study conducted by Pfeifer et al. [33] clearly indicated that the cooling load that can be made available by the fuel cell is much more than that needed by the MH storage system (i.e. to main its hydrogen discharge rate at a desirable level).

Two years later in 2011, Urbanczyk et al. [36] conducted a similar study on a 260-W high-temperature PEM fuel cell stack (28 cells and a membrane effective area of 50 cm^2) and one MH canister with 60 g of hydrogen storage capacity (i.e. enough to operate the fuel cell for 3 h at its rated power). They also used oil as heat transfer medium; however, in this study, a heat exchanger (U-bend tube with thermal oil) was installed inside the MH canister (rather than external heat transfer) to enhance the MH hydrogen discharge rate through applying the heat generated by the PEM fuel cell. As reported by the authors, by transferring 160 W of heat from the fuel cell to the canister, its hydrogen release rate could be enhanced from 2 slpm to about 3.6 slpm (i.e. over 80% increase), enough to meet the fuel cell demand for hydrogen at its rated power (i.e. 260 W).

In 2014, this idea was practiced again by Weiss-Ungethüm et al. [37] on a high-temperature 400-W PEM fuel cell (8 cells and 163.5 cm^2) thermally coupled with a MH canister filled with 300 g of sodium alanate that can absorb 7.8 g of hydrogen. The fuel cell coolant was circulated around the MH canister through the heating coil wrapped around the canister. While canister hydrogen supply rate was not initially sufficient to meet the fuel cell demand at its rated power, the study showed that by transferring the fuel cell heat to the canister, this problem can be addressed and the hydrogen discharge rate of the canister could be enhanced from 4.5 mg/s to 5.8 mg/s, enough to meet the demand of the fuel cell at its rated power.

Study of thermal coupling between PEM fuel cells and MH canisters has not been limited to high temperature PEM fuel cells only. Song et al. [38] and Rizzi et al. [39], for example, have studied such coupling for low temperature PEM fuel cells. Song et al. [38] investigated the idea of thermal coupling between a low temperature (i.e. ~ 50 °C) 5-kW PEM fuel cell and four MH canisters with the capacity of storing 3 kg of hydrogen in each canister. The system used for this study was designed for a mobile light tower application and was significantly larger than the fuel cell systems investigated before (i.e. to study the thermal coupling arrangement between the fuel cell and the MH hydrogen storage system). As for the mechanism for heat transfer, air was used to capture the heat generated by the PEM fuel cell and then this heat was passed on to water (through a heat exchanger) that was circulated around the canisters. It was reported by Song et al. that only 20% of the total cooling load of the fuel cell was demanded by the canisters that helped enhance their hydrogen release rate enough to meet the demand of the PEM fuel cell at its rated power (5 kW) (i.e. the total of 3.45 g/min). Rizzi et al. [39] also conducted an experimental investigation on thermal coupling between a low temperature (i.e. ~70 °C) 760-W PEM fuel cell and six MH canisters (with 400 g of hydrogen storage capacity). In this experiment water was used to extract heat from the PEM fuel cell and transfer that to the canisters. The hot water (i.e. at 67 °C) flew through a heating jacket on each of the MH canisters to maintain their temperature at about 60 °C. Copper fins were attached on the outer surface of the MH canisters in order to increase the heat transfer area. It was concluded in this research that the hydrogen discharge of the canisters could be maintained at the level required by the PEM fuel cell at its rated power. Whereas, without the supply of the fuel cell heat to the canisters they were not capable of catching up (i.e. in terms of hydrogen discharge rate) with the fuel cell hydrogen consumption rate.

In previous studies, mainly active methods (liquid and air) were used for thermal coupling between PEM fuel cells and the MH canisters