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Thermal coupling of PEM fuel cell and metal hydride hydrogen storage using heat pipes

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ABSTRACT

This paper presents a mathematical model to study opportunities for simultaneous passive thermal management of an integrated PEM fuel cell and metal hydrogen (MH) storage system by thermal bridging of these two components, using heat pipes. The thermal coupling arrangement is expected to be promising, because, as more power is drawn from the PEMFC, more heat is generated that can be used to enhance the rate of release of hydrogen from the MH storage. Heat pipes can provide an effective passive thermal bridge for this purpose on account of their high thermal conductivity, and thus avoid parasitic energy penalties associated with active methods of cooling. The main components modelled analytically in MATLAB in this study are the PEMFC, heat pipes, and MH hydrogen storage. This simulation has been used to size the heat pipe system needed for thermal coupling of a 500 W PEMFC and MH storage canisters. The performance improvement of the MH system after receiving the fuel cell heat, and the cooling capacity of the MH system to be used as heat sink for thermal management of the fuel cell stack, has been studied. The MH canisters used to supply hydrogen to this stack each had the maximum supply capability of 2.5 slpm at 25 °C, while the fuel cell demand was 7.2 slpm at its rated power (500 W). The results show that just under 20% of the total cooling load of the stack (i.e. ~880 W) at its maximum power point is demanded by the MH canisters (~170 W) to achieve the required hydrogen discharge rate of 7.2 slpm at 35 °C provided the MH canisters are thermally well insulated.

Introduction

Proton Exchange Membrane Fuel cell (PEMFC) is a device in which hydrogen (as fuel) and oxygen (can be from air) react electrochemically and the result of this reaction is the generation of electricity, heat, and water [1]. Although the efficiency of a PEMFC in generating electricity is relatively high (up to 55% based on high heating value of hydrogen), still substantial amount of heat is generated as by-product that must to be effectively removed from the fuel cell in order to maintain its temperature at a desirable level [2–4]. PEMFCs usually operate at a relatively low temperatures, usually in the range of ~60–80 °C [2], that makes this type of fuel cell a suitable option for many stationary and mobile applications where particularly quick start-up is essential [5–7]. The heat

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generated during the operation of PEM fuel cells can be extracted and used in a range of heating applications (e.g. hot water supply, space heating, or heating up the inlet reactants in cold climate conditions) together with the power generated by the fuel cell [2,8–11].

In many applications, a metal hydride (MH) hydrogen storage is used to supply hydrogen to the fuel cell. Obtaining a sufficient release rate of hydrogen from the MH storage system at normal ambient temperatures (e.g. 20–30 °C) to supply the PEM fuel cell at its maximum power point is often a technical challenge [12–14]. The simple solution of oversizing the MH storage system to achieve the required rate of hydrogen release is undesirable economically.

Heating up the MHs and operating them at a higher range of temperature (i.e. above normal ambient temperatures) can increase the hydrogen release rate of the MHs quite considerably [15]. This behaviour can guide us toward a more advanced solution to the above-mentioned problem: using the heat normally rejected from the fuel cell to raise the temperature of the MH storage system and enhance its hydrogen release rate [14,16,17].

The heat from the fuel cell can effectively be transferred to MH storages using heat pipes, as suggested previously by some researchers [18–20]. Heat pipes have a very high equivalent thermal conductivity and can transfer a large amount of heat from the fuel cell to the MH storage with no additional pumping power required. In turn, heat pipes come with other advantages such as simplicity and lower maintenance costs because of having no moving parts in their structure, while they can provide an excellent temperature controlling mechanism compare to many other passive cooling methods [21]. This is due to the fact that they operate based on a set equilibrium pressure and the boiling point (at this set pressure) of a certain liquid used in the heat pipe.

Heat pipe solutions have also been suggested and studied before for thermal management of MHs, i.e. in order to reduce the charging/discharging time and to enhance the exothermic/endothermic reaction between the hydrogen molecules and metal powder [22–24]. However, although heat pipe solution has been used before for thermal management of MHs and PEM fuel cell separately, the possibility of thermal coupling of a PEM fuel cell and MH hydrogen storage using heat pipes has not been studied before. While thermal coupling of a PEM fuel cell and MH hydrogen storage system has been investigated before by several researchers [13,25,26], all these earlier studies employed active heat transfer methods such as water and air circulation, all involving parasitic energy consumption.

This paper focuses on a mathematical modelling to describe and study the performance of the novel arrangement of simultaneous cooling of PEM fuel cells and heating a metal hydride hydrogen storage using a passive heat pipe system for heat transfer. The following section focuses on reviewing literature on the possibility of using heat pipes for PEMFC cooling and also thermal management of MHs, including previous research on active thermal coupling of PEMFC and MHs. Next section focuses on a mathematical model developed as part of this study is described, and a case study of a PEMFC and a MH hydrogen storage being thermally coupled using heat pipes is reviewed by applying the created model. Finally, last section provides some conclusions and recommendation for further studies.

Opportunities for thermal coupling of metal hydride hydrogen storage and PEM fuel cells

An overview

As already discussed in the introduction part due to inefficiencies associated the fuel cell, part of the energy content of hydrogen appears in the form of heat [2]. Thus, a proper cooling system is required in order to maintain the stacks temperature at a desired level that is ~60–80 °C for PEMFCs [27–29] or up to 100 °C in some high temperature PEMFCs [30]. In general fuel cell cooling can be done using either passive methods (e.g. heat spreader or heat pipes) [19] or active methods (e.g. liquid cooling, fan, and forced air cooling) [31] depending on the size and operating condition of the fuel cell. Liquid cooling is generally employed in high power PEMFCs (e.g. above 5 kW), such as those used in automotive applications [4].

In some fuel cell applications, MH systems are used to store and supply hydrogen to the fuel cell. A MH hydrogen storage unit includes a canister filled with special metal alloys (M) that can form weak bonds with hydrogen (H), at usually not a very high pressure (e.g. 10–40 bar). In other words MH stores hydrogen gas in atomic form as a chemical combination called MH. These weak bonds can be broken by applying heat (mostly absorbed from atmosphere at normal ambient temperatures) while the MH is exposed to low atmospheric pressure. The charging and discharging are exothermic and endothermic reactions respectively; hence, proper thermal management of MHs can improve their hydrogen absorption and desorption performance. In particular applying heat to enhance the discharge characteristics of MH (i.e. through external or internal heat transfer to the MH canisters) has been practiced, studied, and demonstrated by many researchers before [25,32–35].

A MATLAB/Simulink model that was developed by Hyeong Cho et al., 2013 [36] analysed the effect of an external water channel temperature to enhance the hydrogen discharging flow rate in a MH canister (i.e. with the capacity of storing 1.43 kg of hydrogen). The test was performed for 10,000 s at the initial pressure of 10 bar using different water temperature with the variations of 20, 30, and 40 °C. The hydrogen discharging rates of 0.2, 0.4, and 0.6 kg/h were achieved, respectively using those temperature variations. Based on the results, the authors confirmed that a higher water circulation temperature facilitates a higher hydrogen discharging flow rate.

The heat can be transferred to a MH canister using two methods: internal and external [37]. Example of internal heat transfer arrangement is that practiced by Mellouli et al., 2007 [16] who equipped a metal hydride reactor with a spiral type heat exchanger to provide more heat transfer area. Also in another case study a capillary tube bundle heat exchanger with a large heat transfer surface inside the metal hydride hydrogen storage was used by Linder et al., 2010 [38]. In both