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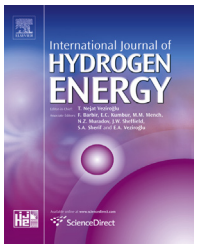

Experimental comparison between external and internal humidification in proton exchange membrane fuel cells for road vehicles

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ABSTRACT

In this paper, the humidification issues of proton exchange membrane (PEM) fuel cells were experimentally analyzed using three fuel cell systems (FCSs) based on stacks of different sizes (2.4, 6.2 and 14 kW). Both internal and external humidification strategies were considered. External humidification was performed on the air stream using the following techniques: air saturation at different temperatures (bubbler), water injection into the cathode manifold and heat and mass exchange by selective polymeric membranes. The internal humidification analysis focused on the self-humidification approach. The effect of humidification strategies on membrane hydration was evaluated by analyzing the stack performance and its power loss rate.

The external humidification strategy was effective at most operative conditions, but it exhibited limitations at typical conditions which favored membrane dry-out (i.e., low load and high stack temperature). At a high load and temperature, the external humidification was effective when the saturation temperature of the inlet air stream was maintained at values close to the stack temperature (temperature difference < 5 K). The self-humidification technique was shown to be the most practical choice for application in hybrid fuel cell vehicles, though it requires accurate control of the stack temperature profile in the range of 303–328 K for normalized powers (P/P_{max}) between 20 and 90%.

Introduction

Hydrogen fuel cell systems are extremely promising on-board power generators for road vehicles [1] because they can achieve a high powertrain efficiency with low CO_2 emissions due to the fuel electrochemical conversion; these systems are also pollutant-free because pure hydrogen is used as fuel. In addition, there is strong research interest for fuel cell systems being utilized in range-limited electric vehicles, which currently use traditional energy storage systems [2,3]. PEM fuel cells are most suitable for transportation applications due to their low operative temperature, rapid start-up, high efficiency, good transient response, and lack of corrosive liquid electrolytes [4].

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In a PEM fuel cell, the polymeric membrane electrolyte operates at temperatures between 300 and 360 K, and hydration must be properly maintained to guarantee satisfactory ion conductivity. The strong correlation between proton conductivity and the water content of Nafion, which is the material used as the membrane in PEM fuel cells, has been verified [5].

The necessity of adequate membrane humidification involves the risk of flooding, whereas evaporation can cause dry-out; thus, the stack operative conditions must be carefully tuned to avoid both of these phenomena [4]. Because water produced by the electrochemical reaction is initially in the vapor phase, membrane hydration occurring in this phase is more relevant with respect to water uptake from the liquid phase. Unfortunately, the water produced at the cathode side and the air moisture could be insufficient to ensure that the membrane is properly wet at all working conditions because of the complex phenomena involving water within the membrane electrode assembly (MEA) [6–8]. Moreover, the water removal capacity of reactant streams withdraws part of the water from the cell module in quantities that exceed the water produced by the electrochemical reaction, particularly at high temperatures. The wet air stream temperature typically remains lower than the local surface temperature of the electrode; thus, the evaporation rate is high and causes membrane dry-out. Furthermore, low humidity conditions have been found to rapidly degrade Nafion-like membranes [9].

However, an excess of liquid water in contact with the membrane can cause flooding, which strongly decreases its proton conductivity [10]. If flooding occurs, it is necessary to perform a hydrogen feeding procedure or to control the air flow rate to drain the water excess in both the anode and cathode compartments. The purge valve in the fuel feeding circuit should be opened with different frequencies or delays, and the air flow rate should be varied to modify the stoichiometric ratio.

However, the primary goal of the water management strategy is to avoid the dry-out phenomena, which requires developing proper strategies to maintain an adequate humidity level within the membrane during all FCS operative conditions.

The PEM fuel cells can be humidified using either internal or external methodologies. External humidification implies a modification of the feeding stream humidity ratio and helps to balance the combined effects of electro-osmotic drag and back diffusion, which can maintain the membrane performance. Among the practical solutions, one possibility is saturating the reactants at different temperatures before they enter the stack [11]. High temperatures allow the absorption of a significant amount of water in gas streams and its transport inside the stack to compensate for the water losses due to rapid internal evaporation. However, the primary problem with external humidification is that the gas cools after the humidifier device; then, the excess water could condense and enter the fuel cell in droplet form, which floods the electrodes near the inlet and thereby prevents reactant flow.

Most common humidifier devices are primarily used for air hydration; these devices are more rarely used for hydrogen stream. Humidifier devices are based on bubblers, water evaporators, enthalpy wheels, pumps for liquid water injection, or membranes. Membrane humidifiers represent an interesting passive solution, i.e., different from other devices, additional equipment is not required, which thus reduces both the complexity and energy consumption of an FCS [12]. Their operation is based on separation by a semi-permeable polymeric membrane of the dry stream from the other compartment that is crossed by the wet stream. The dry stream can increase its water vapor content along the entire interface area of the membrane from the inlet value up to approximately the saturation value at the exit of the device. An additional simple external method is based on liquid water injection inside the air cathode manifold, which offers the possibility of more flexible water management due to an additional governable parameter [13].

The simplest method of internal humidification is "self-humidification", which is based on the principle that a fraction of the water content of the membrane remains inside the polymeric material and that the water produced by the reaction during stack operation is sufficiently absorbed by the electrolyte [14–16]. No external device is required and internal operative parameters control the membrane humidification, with a management that exclusively exploits the transport mechanisms through the electrolyte.

The complexity of various issues associated with the correct humidification of a Nafion-like membrane requires careful evaluation when the FCS is used as a power source in a fuel cell vehicle, where additional demands are present (cost, size, weight, lay-out simplicity). The objective of the present work is to compare different humidification methodologies (saturation of reactant streams at different temperatures, humidification by selective membranes, water injection into the cathode manifold and self-humidification) in relation to FCS performance, which focuses on the application of hybrid fuel cell propulsion systems. Experimental tests were conducted on three FCSs with different powers, which operate at low pressure and used different humidification strategies.

Experimental

The main technical characteristics of the three FCSs used in the tests are reported in Table 1, whereas an overall scheme is shown in Fig. 1. All systems were based on PEM stacks with different maximum power and number of cells. The FCSs operated at low reactant pressure in a dead-end procedure and were water cooled. High-purity hydrogen was fed by high-pressure cylinders. The fuel line was periodically purged to drain the excess water diffusing from the cathode to the anode side through the polymeric membrane [17]. The diameter of the hydrogen purge valve guaranteed a minimum pressure at the anode inlet (not less than 30 kPa). A side channel compressor was used to feed the cathode side, and the air flow rate was regulated by the air compressor speed in order to control the stoichiometric ratio. Two pressure transducers were located upstream of the stack to monitor the anode and cathode pressures during the experimental runs. To guarantee a uniform temperature through the cells, a temperature difference of less than 5 K was accepted between the inlet and outlet cooling water temperatures. This