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Tools for designing the cooling system of a proton exchange membrane fuel cell

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ABSTRACT

Proton exchange membrane fuel cell (PEMFC) requires a careful management of the heat distribution inside the stack. The proton exchange membrane is the most sensitive element of this thermal management and it must operate under specific conditions in order to increase the lifetime and also the output power of the fuel cell. These last decades, the enhancement of the output power of the PEMFC has led the manufacturers to greatly improve the heat transfer effectiveness for cooling such systems. In addition, homogenizing the bipolar plate temperature increases the lifetime of the system by limiting the occurrence of strong thermal gradients. In this context, using a fluid in boiling conditions to cool down the PEMFC seems to be very suitable for this purpose. In order to compare the thermal performances between a coolant used in single-phase flow or in boiling flow conditions, we have built an experimental set-up allowing the investigation of cooling flows for these two conditions. Moreover, the geometry of the cooling channels is one of the key parameters which allows the improvement of the thermal performances. Indeed, the size or the aspect ratio of these channels could be designed in order to decrease the thermal system response. The sizing of the fuel cell cooling system is of paramount importance in boiling flow conditions because it can modify, not only the pressure losses along the channel and the heat transfer coefficient like in a single-phase flow but also, the onset of nucleate boiling (ONB) and the dryout point or critical heat flux (CHF). Thus, in order to understand some heat transfer mechanisms, which are geometry-dependent, a parametric study was completed by considering flows in four different rectangular channels. Finally, this study allows a better insight on the optimization of the geometrical parameters which improve the thermal performances of a PEMFC, from a cooling strategy aspect point of view.

1. Introduction

For about thirty years, fuel cells have been at the center of many industrial concerns due to their higher performance and their lower environmental impact compared to thermal engines. Moreover, the increase in legal constraints relative to environmental protection and specifically the limitation of greenhouse gases has led the manufacturers to consider low polluting strategies. One of the strategies is to use fuel cells which could allow for the broadening of energy production.

One of the main advantages of operating PEM fuel cells is related to their low running temperature which allows a quick start up, in comparison with other types of fuel cells. However, several drawbacks due to this low running temperature, such as the poisoning of the electrodes by carbon monoxide (CO) or problems of water management have already been reported in the literature [1,2]. There is a very close relationship between thermal management in the stack and operating performances of a PEMFC. Thus to ensure the good operation of a PEMFC each cell should be carefully cooled. This is due to the substantial amount of heat that is generated in each cell by entropy changes and irreversibility during operation. If too much heat is removed, the kinetic of the reaction is adversely affected, resulting in lower stack performance. Conversely, if the stack is allowed to heat up beyond its optimal operation temperature, the membrane dries out and its proton conductivity drops. The control of the membrane water content is therefore also a vital part of the stack management strategy. Intuitively, placing a cooling plate between the successive adjacent cells should allow for a good control of the thermal envelope and ensure nearly identical operational conditions throughout the stack; this, however, would increase the cost, weight, volume, and complexity of the system. In light of this, a careful balance has to be made in designing such a cooling system.

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Usually PEMFCs are operated at a cell voltage of around 0.7 V. At this voltage value, the heat generation is generally high (~20,000 W/m^2) as demonstrated by [3]. Nowadays, high performance PEMFC reach electrical power density of more than 20,000 W/m^2. Correspondingly, a heat flux of more than 20,000 W/m^2 has to be removed from the fuel cell. To extract this heat flux, a cooling medium has to flow through the bipolar plates in order to remove heat by convection. As demonstrated by Ref. [4], important efforts are done to understand where the heat is generated inside the PEMFC in order to define the strategies to manage the temperature in the in-plane and in the through-plane direction. Most PEMFCs which generate significant electrical power (>5 kW) are cooled with liquid and specifically de-ionized water, which is cheap, nontoxic and has a high heat capacity. For such an electrical power, the use of liquid for the cooling becomes necessary. Other working fluids should be considered when the use of water is not possible for given operating conditions (i.e. ambient temperature below 0 °C). The interest in the PEM fuel cells cooling is quite recent as shown by Bigot [5]. Indeed, due to the constant efforts made to reduce the size of the different fuel cell elements, the heat flux which has to be extracted from the core of the PEMFC has increased rapidly. These new conditions have brought about new methods to guarantee the heat load discharge, in order to enhance the fuel cell output performances as shown by Park and Caton [6]. To remove this heat load from the fuel cell, a coolant (liquid or air) flows through channels which are machined at the rear of the bipolar plates. The thermal performances of such a cooling system are mainly based on three criteria which are:

- Management of the heat load in order to avoid drying or flooding of the membrane,
- Control of the pressure drop inside the cooling system,
- Homogeneity of the bipolar plate temperature for a better control of the electrochemical reactions and an increase of the membrane lifetime.

When the heat flux to be removed from the PEMFC increases, it becomes necessary to modify the cooling process in order to guarantee these three previous criteria. Indeed, as demonstrated by Corbo et al. [7], when the output power of their PEMFC became larger than 20 kW, water cooling was more efficient than air cooling. Indeed, as demonstrated by Refs. [8–10] there exists a large temperature non uniformity for high power PEMFC when air is used as a coolant.

A large number of parameters can act on the fuel cell operation and specifically on the cooling system design.

1.1. *Air stoichiometry effect*

The air stoichiometric effect can be important on the fuel cell output performances and on the heat load as demonstrated by Bao et al. [11]. Indeed, the electrical power produced by the fuel cell increases with the air stoichiometry because a higher percentage of oxygen could be used to enhance the electrochemical reaction. Moreover, at the same time, better management of the water inside the membrane has been experimentally observed. The authors showed that an increase of the air stoichiometry allows improvements in the fuel cell heat removal. However, to increase the value of this parameter, the flow rate has to be raised considerably compared to the hydrogen flow rate. This augmentation of the air stoichiometry generally leads to higher pressure drop at the fuel cell cathode side, which could expose the membrane to dryout and pressure stresses. Some holes can appear inside the membrane and thus lower its lifetime [12].

1.2. *Coolant flow rate and condenser efficiency*

Kim et al. [13] have shown experimentally that when the flow rate of the coolant (water for their experiments) inside the cooling loop increases by a factor of 4, while the fan flow rate (which allows the cooling of the coolant inside the condenser) is kept constant, the heat load extracted from the fuel cell is improved by 44%. Nonetheless, if the coolant flow rate is kept constant, the increase of the fan flow rate by a factor of 4 enables an augmentation in the thermal extraction performance by 118% for their experimental conditions. It is important to underline that the fan flow rate efficiency is highly dependent on the ambient (or external) temperature and could drop very quickly if the temperature difference between the fuel cell core and the ambient temperature is too small.

1.3. *Design of the channel fuel cell geometry*

Wang et al. [14] demonstrated that the sizing of the PEMFC channels can have very significant impact on the PEMFC output performances (i.e. output power). We have to point out this result, because the most promising PEMFCs (from an economic point of view) are built with metallic bipolar plates which are easily adjustable. On the same thin metal plate, the gases used for the electrochemical reaction are flowing on one side (core channels) and the coolant used for the thermal management of the fuel cell is flowing on the other side (cooling channels). It is important to emphasize that the choice of the core channels' size dictates the size of the cooling channels. The authors have experimentally demonstrated that the electrochemical reaction is improved when the aspect ratio of the channels at the cathode side decreases. Conversely, they explained that the modification of the channel dimension on the anode side has a lower effect on the fuel cell output performances. Yu et al. [15] have shown numerically that the choice of a multi-pass serpentine path for the cooling channel could have an important impact on the thermal performances of the fuel cell and could highly improve the temperature homogeneity along the walls.

1.4. *Choice between single-phase flow or boiling flow for the cooling strategy*

As presented by Ref. [16], there exist several methods for the cooling of a PEMFC: cooling with heat spreader, cooling with separate air flow, liquid cooling and more recently phase change cooling. All these techniques have their advantages and disadvantages as presented in the Table 1 of Ref. [16].

The choice between single-phase or boiling flow conditions could act have a significant impact on the thermal performances of a PEMFC. A lot of studies have been devoted to the cooling of a PEMFC using coolant in single-phase flow conditions [15,17 among others]. Nevertheless, the heat exchanged is generally higher for a boiling flow than for a single-phase flow, if instabilities are avoided, for the same operating conditions. Moreover boiling flow allows a better thermal homogeneity along the wall compared to single-phase flow. Indeed, for a boiling flow, the fluid temperature cannot exceed the saturation temperature. In order to completely characterize the total operating range for a boiling flow, two important parameters have to be considered:

- the onset of nucleate boiling (ONB) beyond which the prediction tools (pressure drop and heat transfer coefficient) used in single-phase flow are not adequate,
- the critical heat flux (CHF) beyond which the wall temperature could sharply increase and the heat transfer coefficient could decrease due to the incipience of another heat transfer mechanism.