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On the current distribution at the channel – rib scale in polymer-electrolyte fuel cells

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ABSTRACT

Experimental results based on in-situ measurements at the interface between the catalyst layer and the gas diffusion layer (GDL) on the cathode side at the channel – rib scale show an interesting variation of the current density distribution as the mean current density is increased. It is found that the local current density below the rib median axis corresponds to a maximum at low to intermediate mean current densities and to a minimum when the mean current density is sufficiently high. Also, the higher is the current density, the more marked the minimum. From numerical simulations, it is shown that the current density distribution inversion phenomenon is strongly correlated to the liquid water zone development within the GDL.

Introduction

As pointed out in Ref. [1], the current density spatial distribution is of high interest in order to characterize the operation and performance of polymer electrolyte fuel cells (PEFCs). The fact that the current distribution is not uniform is well known, e.g. Ref. [1] and this can cause the loss of performance and contributes to degradation mechanisms leading to a reduced lifetime of the PEFCs [2]. Here, we focus on the current density distribution at the channel – rib scale. We first report experimental measurements showing an interesting variation in the current density distribution when the mean current density is varied. In particular, the measurements indicate a reduced current production under the rib when the mean current density is sufficiently high. This effect is not new. It has been reported in Ref. [3], also from local measurements. As in our experiments, the current density distributions reported in Ref. [3] show that the current density tends to become less and less uniform as the average current is increased and that the minimum current density tends to localize below the rib area. The existence of a minimum current density below the rib has been predicted from numerical simulations, e.g. Refs. [4–13]. Essentially, the phenomenon was explained by the oxygen starvation below the rib. However, the simulations reported in previous works, e.g. Refs.

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[4–13], were all based on various questionable simplifications. In particular, the possible presence of liquid water in the gas diffusion layer (GDL) was completely ignored in the majority of those works. Exceptions are the works presented in Refs. [5,6]. However, the model used in Refs. [5,6] is isothermal and the presented results are actually not consistent with the existing measurements since the current density is predicted to be lower below the rib for any mean current density. On the other hand, the interpretation of the experimental results reported in Ref. [3] was not fully conclusive because the liquid water formation could not be detected. In other terms, the possible impact of the liquid water on the measured current density distributions could not be assessed.

As in previous attempts, e.g. Refs. [4–13], we rely on numerical simulations in order to better understand the changes in the structure of the current density distributions when the mean current density is varied. The significant difference is that we use a model taking into account both the temperature gradients within the GDL and the process of liquid water formation by condensation.

As discussed in Ref. [14], the modeling of transport phenomena in polymer-electrolyte fuel cells can be developed within various frameworks. The most classical one is the continuum approach to porous media in which each porous layer is seen as a fictitious continuum medium. As a recent example where this type of modelling is used, one can refer to [15]. However, as discussed in various articles, e.g. Refs. [16,17] and references therein, the results obtained with the classical continuum approach can be questioned when the approach is applied to thin systems with only a few pores over the thickness, i.e. the GDLs, especially as regards the simulation of two-phase flows. For such thin porous media, a potentially accurate option is to perform direct simulations, e.g. Ref. [18]. However, the computational time associated with this type of method is quite long and the computational domain often quite small. In between, we have the pore network models (PNM). PN modelling is a mesoscale approach based on a simplified representation of the pore space as a network of pores connected by narrower channels (also referred to as throats). The approach can be considered as a good trade-off. Much less computationally demanding than the direct simulation methods, the PNM approach does not suffer from the shortcomings of the continuum approach. In particular, PNMs are well adapted to simulate the capillary-fingering flow regime commonly considered in the modelling of two-phase flows in PEMFC, e.g. Ref. [19]. This explains why PNM is now a somewhat popular approach for modelling two-phase flows in GDL, e.g. Refs. [17,20,21], where numerous references are given. Whereas the study of two-phase flows in GDL using PNM has been often performed in the past without explicit coupling with the other transport phenomena, it can be noted that this coupling is taken into account in more recent works, e.g. Refs. [17,20,22,23]. Actually, the idea in those works is to combine the continuum approach where it is appropriate, i.e. for the catalyst layer (CL), the microporous layers (MPL) and the membrane, with pore network modelling for the layers where PNM is clearly more appropriate, i.e. the fibrous layer of the GDLs. In line with this state of the art, we use for the simulations in the present paper the coupled continuum – PNM model described in Ref. [20]. This model of a PEMFC cathode couples the electro-chemical phenomena taking place in the catalyst layer with a pore network model (PNM) for computing the transfers and the liquid water formation in the fibrous diffusion medium (DM) of the GDL and a continuum approach in the MPL. As emphasized in Ref. [20], distinguishing features of this PNM are to assume that the water forming in the CL enters the GDL in vapor form and to model the liquid water formation by condensation in the DM.

Actually, it was already shown in Ref. [20] that the current density distribution predicted by the model was different under dry condition (no liquid water in GDL) and wet condition (liquid water in GDL) with the localization of the minimum current density below the rib for the wet conditions, thus qualitatively as in the existing measurements. However, the current density distribution was shown for only one mean current density for the wet condition. Here, the current density distributions will be presented over a much larger range of mean current densities so as to establish a much clearer correlation between the liquid water formation and the change in the current density distribution. Also, no experimental results on the current density distributions were presented in Ref. [20].

The article is organized as follows. The experimental results of interest are briefly presented in the next section. Then some basic features of the modelling are recalled. Main results of simulations are then presented both as regards the current density distribution and the liquid water distribution. A discussion is proposed before the conclusion.

Experiments

The measurement method is along the same lines as the one described in Ref. [3]. It is based on a reverse method exploiting the measurement of electrical potential in the membrane electrode assembly (MEA) core with thin tungsten wires of 25 μm placed at 115 μm from each other at the interface of the catalyst layer and the microporous layer. One can refer to [24] for a detailed description of the experimental set-up and measurement methods. It is important to note that those measurements were performed at a fuel cell standard operating temperature of 80 °C. Here also it was not possible from the experiments to relate the current density minimum localization with the possible impact of liquid formation. The main results obtained in Ref. [24] and of interest for the present study are shown in Fig. 1.

As can be seen from Fig. 1, the transverse current densities distribution varies with both the relative humidity *(RH)* in the channel and the mean current density $\bar{i}$. For the three *RH* tested, the transverse current density is uniform over the CL-GDL interface for a sufficiently low mean current density (approximately $\bar{i} < 0.2$ A/cm^2). Then, as the mean current density is increased, the local current density tends to be slightly higher in the region of the CL-GDL interface located below the rib than below the channel (this corresponds to mean current densities approximately in the range [0.2–0.6 A/cm^2]). This trend is reversed in the range of the highest mean current densities ($\bar{i} > 0.6$ A/cm^2). The local current density is then significantly lower in the region of the interface located below the rib. As can be seen also from Fig. 1, the non-uniformity of

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