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On modifying the condition for the local current density decoupling in fuel cell stacks for moderate perturbations

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ABSTRACT

Two adjacent cells in a fuel cell stack are said to be decoupled when they do not affect each other's local current density distribution. This paper proposes a condition for local current density decoupling between two adjacent cells with arbitrary degree of perturbations. The proposed condition in the form of a bound comprising some measure of the perturbation on a dimensionless number comprising the design, operating conditions, and material properties of the bipolar plate is correlated with the current redistribution between cells and verified with a non-isothermal proton exchange membrane fuel cell stack model.

1. Introduction

A fuel cell stack can comprise in the range of two to several hundred single cells depending on the power and voltage requirements. Although all the cells in a stack have to exhibit the same total current, they do not necessarily behave the same for several reasons: imperfections during manufacturing [1–3], a non-uniform inlet flow distribution due to the external manifold design [4–7], degradation of one or more cells [8] and external boundary conditions, such as heat transfer with the surroundings. Dissimilar local current density distributions in two adjacent cells give rise to in-plane currents and electric potential gradients (x-direction in Fig. 1) in the bipolar plate between them [9]. If the design of the bipolar plates and operating conditions of the stack do not allow for sufficient redistribution of the current, the local current density distributions in adjacent cells will start to influence and perturb each other.

It is of interest to quantify when the local current density distributions in adjacent cells do not affect each other for the following two key reasons [10]: it allows for faster simulation of the stacks [11,12]; it does not allow the disturbance in one cell to propagate to the neighbouring cells [13]. The local current density coupling/decoupling of the cells has been explored earlier [7,10,13–20]. In this regard, Kulikovsky [13] and Sharma et al. [10] concluded with aggregate measures to quantify the local current density decoupling in fuel cell stacks; however, both of these studies deal with some form of worst-case scenario, e.g., current-free spot [13]; opposite extremes of cathode stoichiometries [10]. We note that it has been shown that the condition derived by Kulikovsky [13] and Sharma et al. [10] are equivalent and can be transformed from one another [12].

The aim of this paper is to generalize such studies from the limiting case (e.g., current-free spot; opposite extremes of stoichiometries) to any arbitrary degree of perturbations (e.g., two moderately different stoichiometries). In this regard, we hypothesize the condition for the local current density decoupling from the basic understanding of the current redistribution by the bipolar plate. A verification study is then carried out in the context of a validated non-isothermal model for a proton exchange membrane fuel cell (PEMFC) stack.

2. Hypothesis

We begin by recapitulating the condition for local current density decoupling derived by Sharma et al. [10] (see Fig. 1 for schematic of a 2-cell stack)

$$\Theta \equiv \frac{L^2 i_{\text{app}}}{h\sigma E^{\text{rev}}} \ll 3 \tag{1}$$

where L is the length of the cell, i_{app} is the applied current density, E^{rev} is the reversible cell potential, h and σ are thickness and electric conductivity of the bipolar plate, respectively. The above condition is derived for the limiting case, e.g., Sharma et al. [10] considered

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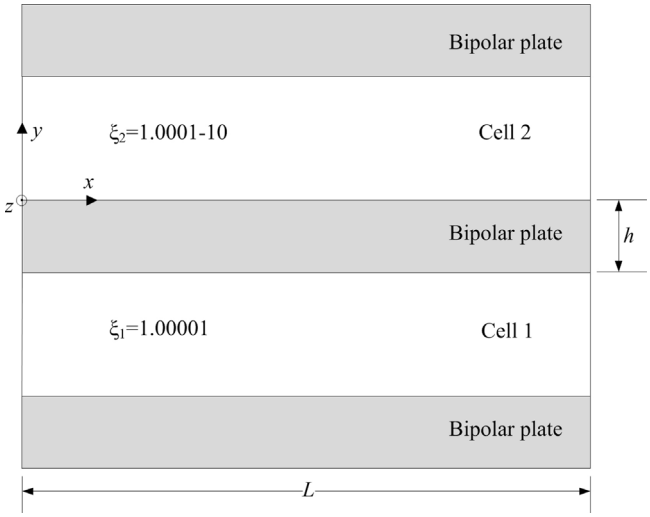

Fig. 1. Schematic of a 2-cell stack operating at different stoichiometries.

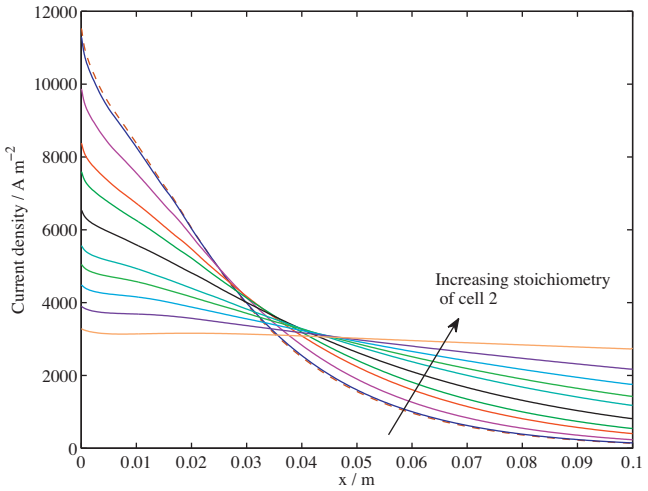

Fig. 2. Local current density distributions in a decoupled 2-cell stack at a stack voltage of 1.2 V. The stoichiometry of the first cell (dashed line) is kept constant at 1.00001 whereas the stoichiometry of the second cell (solid lines) is varied between 1.0001 and 10.

opposite extremes of stoichiometries, i.e., $\xi_c \to 1$ for one cell and $\xi_c \to \infty$ for another cell. If the two cells are completely decoupled or assumed to operate *isolatedly*, the current density distribution corresponding to $\xi_c \to 1$ assumes the form of a Dirac delta function whereas a uniform current density distribution corresponds to $\xi_c \to \infty$. Thus, the current distribution in one cell is highly different from that of another, i.e., $R^2 \sim 0$. Here, R^2 is the coefficient of determination of the current density distributions of the two cells given as

$$R^2 = \max\left(1 - \frac{\int_0^L (I_1(x) - I_2(x))^2 dx}{\int_0^L \left(I_1(x) - i_{app}\right)^2 dx}, 1 - \frac{\int_0^L (I_1(x) - I_2(x))^2 dx}{\int_0^L \left(I_2(x) - i_{app}\right)^2 dx}\right) \quad (2)$$

where $I_1(x)$ and $I_2(x)$ are current density distributions of the first cell and second cell evaluated assuming they are operated *isolatedly*. For an arbitrary degree of perturbations among the cells ($0 < R^2 < 1$), we hypothesize the condition for local current density decoupling as

$$\Theta \ll \frac{3}{1 - R^2} \quad (3)$$

Let us test the above hypothesis for two simple cases:

1. When the two adjacent cells do not have any perturbation, i.e., they exhibit a similar local current density distribution ($R^2 \sim 1$), the condition for the decoupling would have a very large number on RHS. In such a case, the bipolar plate need not to do any redistribution of the current whence a bipolar plate made of any arbitrary dimensions and material would satisfy the condition for local current density decoupling of the cells.
2. When the two adjacent cells have large perturbations, i.e., they exhibit highly different current density distribution ($R^2 \sim 0$), the condition for the decoupling would be simply $\Theta \ll 3$. The condition derived by [13,10] is thus a subset of the condition hypothesized here.

3. Verification

In order to verify the hypothesized condition and its relevance, we proceed by considering a two-dimensional PEMFC stack model. In essence, the PEMFC model [21] solves for conservation of mass, momentum, species, energy, and charge in the functional layers of the cell: bipolar plate, flow field, porous backing, catalyst layer and membrane. For the sake of brevity, we refer to our earlier work [21] for further details on the mathematical formulation and parameters.

Let us consider the flow maldistribution of the reactants [4–7] as the reason for dissimilar current distributions in the two adjacent cells and note that the derivation would still hold for other factors giving rise to the variation. Let us take an example of a two-cell stack where the first cell operates at cathode stoichiometry of 1.00001 and cathode stoichiometry of the second cell is varied between 1.0001 to 10. We proceed with a bipolar plate satisfying the condition for worst-case scenario, $\Theta \ll 3$; the bipolar plate is made out of stainless steel with an electrical conductivity on the order of 10^6 S m^{-1}, and a thickness and length of 10^{-3} m and 10^{-1} m respectively, whence $\Theta \ll 3$ for typical fuel cell operating conditions, i.e., $E^{rev} \sim 1$ V and $i_{app} \sim 10^3$ A m^{-2}. Since we have taken a bipolar plate satisfying the condition for worst-case scenario, the two cells operating at different cathode stoichiometries should exhibit completely decoupled (different) local current density distributions [10]. This is indeed the case as can be inferred from Fig. 2, which presents the current density distributions of the first cell and second cell (at different stoichiometries) at a stack voltage of 1.2 V, corresponding roughly to around 0.6 V for each cell (a typical operating point for the PEMFC) and operating current density, i_{app} of 3×10^3 A m^{-2}. The difference in the two current density distributions gives different values of R^2 as shown in Fig. 3.

Let us continue with three different scenarios having R^2 values of 0.1, 0.7, and 0.9 corresponding to the second cell operating at stoichiometry of 3.1, 1.1, and 1.03, respectively and the first cell operates at stoichiometry of 1.00001 (say, case I-III, respectively).

- For case I ($R^2 \sim 0.1$), our hypothesis gives the following condition for the decoupling:

$$\Theta \ll \frac{3}{1 - R^2} \sim O(10^{0.5}). \quad (4)$$

Hence, the current density distributions of the two cells should affect each other only when $\Theta \gtrsim O(10^{-1.5})$ which is not much less than $10^{0.5}$ (we take $A \ll B$ if A is two orders of magnitude smaller than B). This can be inferred from Fig. 4 presenting the local current density distribution of the second cell operating at stoichiometry of 3.1; the local current density distributions of the cell corresponding to $\Theta \sim O(10^{-3} - 10^{-2})$ overlap the distribution assuming the cell to operate *isolatedly* (maximum relative error