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Short communication

Voltage loss in bipolar plates in a fuel cell stack

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Abstract

Voltage loss in the bipolar plate (BP) is induced by in-plane current in the BP, which arises when the distributions of local current density over the surfaces of adjacent cells are different. We show that potential of BP satisfies Poisson equation with the right side proportional to the difference of local current densities on both sides of BP. Solution to this equation is obtained for BP between two hydrogen cells with the single straight channels and ideally humidified membranes. The general relation for voltage loss in the BP is derived.

Keywords: Fuel cell modeling; Voltage loss; Bipolar plate

1. Introduction

Bipolar plates (BPs) separate individual cells in a fuel cell stack. Each BP distributes reactants over the cell surface through the system of channels, collects current produced by individual cell and transports this current from one cell to another. BPs account for about 80% of the stack weight and 45% of its cost [1]; for these values alone it is clear that BP is one of the key stack components.

In this work we will focus on a third function of BPs in the list above, i.e., on their duty to transport current from one cell to another. In stack modeling it is usually assumed that current crosses BP only in the through-plane direction (see e.g. [2]). This, however, is the case only when the distributions of local current over the surfaces of adjacent cells are the same. However, due to various factors (different stoichiometries of feed molecules in the cells, local "spots" of contact resistance, CO_2 bubbles in DMFC etc.), these distributions are usually different. Local balance of current in the through-plane direction then is not fulfilled and significant amount of current produced by the cells flows along BP (in-plane current). This current results in voltage loss in BP; calculation of this loss is the subject of this work.

It is worth mentioning that local voltage drop between the two bipolar plates is equal to the local cell voltage. Therefore, in-plane currents in the BPs change the distribution of the anode and the cathode polarization voltages over the cell surface. In other words, the problem of voltage distribution in the BPs is coupled to the problem of overpotentials distribution in the cells. Rigorous approach to stack modeling thus requires solution of equation for BP voltage together with a complete problem for individual cells.

Voltage loss in the BP depends on the distribution of plate potential: the more non-uniform this distribution the larger the voltage loss (see below). Generally, to calculate voltage loss we have to calculate plate potential first.

Direct approach to this problem is as follows. Potential of BP obeys three-dimensional (3D) Laplace equation; the boundary conditions for this equation provide the distributions of local current density over the surfaces of adjacent cells and the absence of current through the face planes of BP (see e.g. [3], where 2D analog of this approach is used to calculate voltage loss in the segmented current collector of a single cell).

Below we will show that potential of a thin BP obeys 2D Poisson equation with the right side proportional to the difference of local current densities in the adjacent cells. In the case of BP separating two cells with the single straight channels the problem is reduced to 1D Poisson equation. Solution of 2D or 1D equation is much simpler than managing 3D problem; in a 1D case the analytical solution can be derived.

2. Voltage loss in the bipolar plate

2.1. General assumptions

The thickness of BP ($\simeq$1 mm) is typically 2 orders of magnitude smaller than its characteristic in-plane size ($\simeq$10 cm). The

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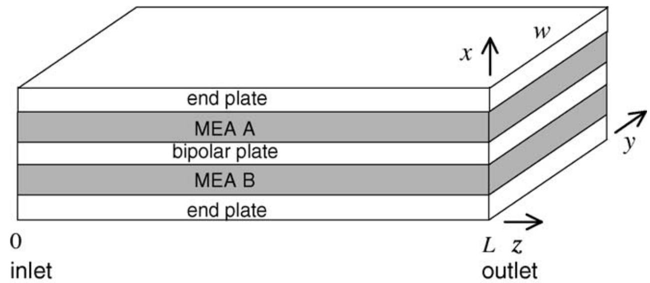

Fig. 1. Sketch of the 2-cells stack with the large aspect ratio $L \gg w$.

variation of potential across the plate can thus be neglected and we may safely assume that in-plane current in the BP induces the variation of plate potential only along the BP surface. For simplicity we will ignore the details of BP geometry (channel/rib structure) and consider rectangular BP of a thickness h_p.

We will assume that in the membrane-electrode assembly (MEA) current flows only in the through-plane direction. Our simulations [5] show that the fraction of current, which flows "along" the MEA is usually indeed negligible.

2.2. Quasi-1D stack

To derive an equation for BP potential and to calculate the respective voltage loss consider first the simplified system: the 2-cells stack formed by the two identical cells A and B with the single straight channels on both sides (Fig. 1). In this stack the length of the bipolar plate L is much larger than its width w, $L \gg w$ (Fig. 1). Since $L \gg w$, we may neglect non-uniformity of current along the y-axis and consider the variation of plate potential only along the z-axis (Fig. 1). Physically, each cell in our stack is quite analogous to that considered in [4].

To understand the origin of voltage loss consider the following problem. Let local current density j_A in the cell A linearly decreases with z and j_B in the cell B is constant (Fig. 2).

As in real stacks, the total currents in the cells A and B are the same: $w\int_0^L j_A\,dz = w\int_0^L j_B\,dz = JLw$, where J is the mean current density in the stack. However, since $j_A(z) \neq j_B(z)$ there is no local balance of the through-plane current. In other words, local current generated in the cell A cannot reach load resistor moving only in the through-plane direction (Fig. 2). Part of j_A must be redistributed along $\tilde{z}$ to match the shape of current in the cell B. This redistribution occurs in the BP and induces the variation of BP potential along z.

To calculate voltage drop along the BP we note that it is the *the difference* $j_A - j_B$, which has to be redistributed along z. Elementary current $(j_A - j_B)w\,dz$ entering the plate near the point a must be transported along the plate to the point a' to provide the balance of local currents at a and a' (Fig. 2). The respective elementary potential drop between a and a' is $\delta V_{aa'} = ((j_A - j_B)w\,\delta z)(2(z_0 - z)r)$, where $2(z_0 - z)r$ is the total resistance of the plate between a and a', r is the linear resistivity of the plate ($\Omega\,cm^{-1}$) and $z_0 = L/2$.

Since $j_A - j_B$ in Fig. 2 is an odd function of $z - z_0$, potential of BP at $z = L$ is

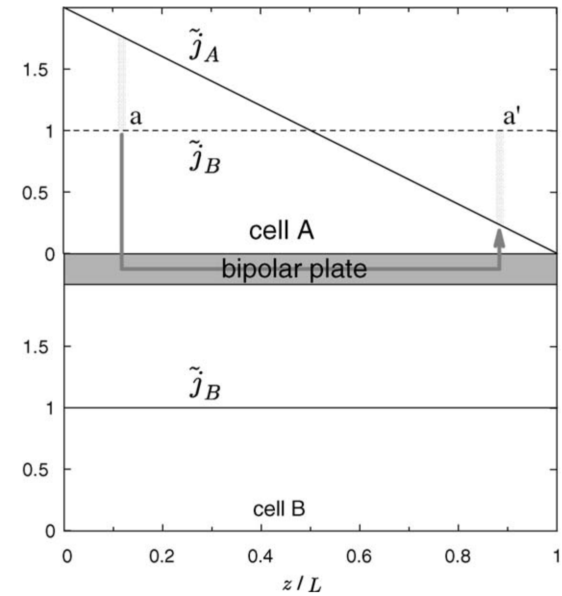

Fig. 2. To the direct calculation of voltage drop along the bipolar plate. Local current in the cell A linearly decreases with z; in the cell B local current is constant.

$$V(L) = \int_0^{z_0} \delta V_{aa'} = 2wr\int_0^{z_0}(j_A - j_B)(z_0 - z)\,dz \tag{1}$$

It is convenient to introduce dimensionless variables

$$\tilde{z} = \frac{z}{L}, \quad \tilde{j} = \frac{j}{J}, \quad \tilde{V} = \frac{V}{RJ} \tag{2}$$

where

$$R = L^2 wr = \frac{L^2}{h_p \sigma} \tag{3}$$

is the plate resistivity ($\Omega\,cm^2$). Here h_p is the plate thickness and σ is the in-plane conductivity of the plate material ($\Omega^{-1}cm^{-1}$).

Calculating dimensionless form of integral (1) with $\tilde{j}_A = 2 - 2\tilde{z}$, $\tilde{j}_B = 1$ (Fig. 2) we find

$$\tilde{V}(1) = \tfrac{1}{6} \tag{4}$$

In the odd case (Fig. 2) we know in advance that $(j_A - j_B)w\,dz$ has to be transported from a to the symmetrical point a'. In the general case of arbitrary j_A and j_B these simple geometrical arguments do not work and a general equation for plate potential has to be derived.

2.3. Equation for bipolar plate potential

Consider the voltage drop δV in the plate on the interval dz near the point z. Clearly,

$$\delta V = Ir\,\delta z \tag{5}$$

Here $I(z)$ is the total current, which flows along the plate at z and $r\,dz$ is the resistance (Ω) of the domain dz. Current $I(z)$ is the sum of currents $j_A - j_B$ entering the BP at all points between 0 and z:

$$I(z) = w\int_0^z (j_A - j_B)\,dz' \tag{6}$$

Note that here j_A and j_B are the algebraic values, which are positive when directed along the normal to the BP surface and negative otherwise.

Using (6) in (5) we find

$$\frac{\partial V}{\partial z} = rw \int_0^z (j_A - j_B)\,dz' \tag{7}$$

Differentiating (7) with respect to z we come to

$$\frac{\partial^2 V}{\partial z^2} = wr(j_A - j_B) + I\frac{\partial r}{\partial z} \tag{8}$$

We see that potential of linear bipolar plate obeys Poisson equation. If r is constant, Eq. (8) simplifies to

$$\frac{\partial^2 V}{\partial z^2} = wr(j_A - j_B) \tag{9}$$

The boundary conditions for (8) and (9) are

$$V(0) = 0, \quad \left.\frac{\partial V}{\partial z}\right|_{z=0} = 0 \tag{10}$$

The first condition establishes the reference point for V; the second one follows from (7) and expresses the absence of normal current through the end face of BP.

In dimensionless variables Eq. (9) transforms to

$$\frac{\partial^2 \tilde{V}}{\partial \tilde{z}^2} = \tilde{j}_A - \tilde{j}_B \tag{11}$$

With (11) in hand we can calculate the distribution of potential along the plate for the currents in Fig. 2. Using $\tilde{j}_A = 2 - 2\tilde{z}$ and $\tilde{j}_B = 1$ in (11) and integrating we get

$$\tilde{V}(\tilde{z}) = \tfrac{1}{2}\tilde{z}^2 - \tfrac{1}{3}\tilde{z}^3$$

At $\tilde{z} = 1$ we get $\tilde{V}(1) = 1/6$, which coincides with (4).

2.4. Potential of the two-dimensional plate

Eq. (9) can be generalized to the case of 2D plate. In this Section we will derive the respective equation in a more straightforward way.

Consider small element of the bipolar plate (Fig. 3). Note that in this Section the BP surface is located in the x–y plane. Suppose that the local currents in the adjacent cells A and B are directed as shown in Fig. 3. Balance of currents in the element reads (Fig. 3)

$$j_E h_p\,\delta y - j_W h_p\,\delta y + j_N h_p\,\delta x - j_S h_p\,\delta x = (j_B - j_A)\,\delta x\,\delta y \tag{12}$$

Note, that positive is the current directed along the normal to the surface of plate element.

Dividing both sides of (12) by $\delta x\,\delta y$ and noting that $j_E - j_W = \delta j_x$, $j_N - j_S = \delta j_y$, where j_x and j_y are x- and y-components of in-plane current density, we get

$$\frac{\partial j_x}{\partial x} + \frac{\partial j_y}{\partial y} = \frac{j_B - j_A}{h_p} \tag{13}$$

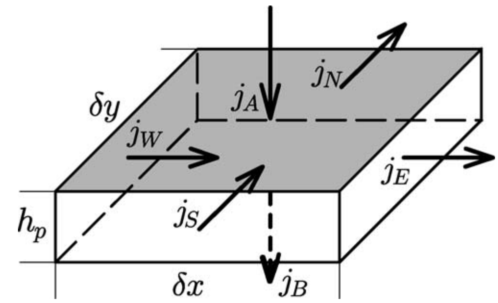

Fig. 3. To the derivation of equation for potential of 2D plate.

According to Ohm's law $j_x = -\sigma\,\partial V/\partial x$ and $j_y = -\sigma\,\partial V/\partial y$; for the plate potential we thus find

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = \frac{j_A - j_B}{h_p \sigma} \tag{14}$$

Since $wr = 1/(h_p\sigma)$, Eq. (14) is the 2D generalization of Eq. (9).

For the 2D plate the natural space scale is the plate thickness h_p, rather than w. Introducing dimensionless variables

$$\hat{x} = \frac{x}{h_p}, \quad \hat{y} = \frac{x}{h_p}, \quad \hat{j} = \frac{j}{J}, \quad \hat{V} = \frac{V\sigma}{Jh_p} \tag{15}$$

we finally get[1]

$$\frac{\partial^2 \hat{V}}{\partial \hat{x}^2} + \frac{\partial^2 \hat{V}}{\partial \hat{y}^2} = \hat{j}_A - \hat{j}_B \tag{16}$$

Normal current through the end faces of the plate is zero; we thus have the following boundary conditions for Eq. (16):

$$\left.\frac{\partial \hat{V}}{\partial \hat{x}}\right|_{\hat{x}=0,\hat{L}_x} = 0, \quad \left.\frac{\partial \hat{V}}{\partial \hat{y}}\right|_{\hat{y}=0,\hat{L}_y} = 0.$$

Here L_x and L_y are the plate sizes along the x- and the y-axis, respectively. These conditions determine $\hat{V}$ within an additive constant; the latter can be defined assigning arbitrary potential to any point of the plate, e.g. taking $\hat{V}(0, 0) = 0$.

2.5. Voltage loss due to in-plane current in the bipolar plate

To derive the general expression for voltage loss in the BP we replace the BP with the equivalent resistor, which dissipates the same electric power and transports total current JS in the system, where S is the BP surface area.

Consider first the quasi-1D plate; total electric power dissipated in the plate is

$$P = \int_0^L I\frac{\partial V}{\partial z}\,dz = \frac{1}{r}\int_0^L \left(\frac{\partial V}{\partial z}\right)^2 dz \tag{17}$$

Voltage loss on the equivalent resistor is thus

$$V_{loss} = \frac{1}{rJwL}\int_0^L \left(\frac{\partial V}{\partial z}\right)^2 dz$$

[1] Note that $\tilde{j} \equiv \hat{j}$.

In dimensionless variables (2) the latter equation transforms to

$$\tilde{V}_{\rm loss} = \int_0^1 \left(\frac{\partial \tilde{V}}{\partial \tilde{z}}\right)^2 \,{\rm d}\tilde{z} \tag{18}$$

In view of (7), which in dimensionless variables is $\partial\tilde{V}/\partial\tilde{z} = \int_0^{\tilde{z}} (\tilde{j}_{\rm A} - \tilde{j}_{\rm B})\,{\rm d}\tilde{z}'$, Eq. (18) is equivalent to

$$\tilde{V}_{\rm loss} = \int_0^1 \left(\int_0^s (\tilde{j}_{\rm A} - \tilde{j}_{\rm B})\,{\rm d}\tilde{z}\right)^2 {\rm d}s \tag{19}$$

Thus, in a 1D case the voltage loss can be calculated not solving the problem for BP potential. Note, however, that numerical solution of Eq. (11) and subsequent calculation of integral (18) can be faster than the calculation of double integral (19).

In 2D case Eq. (18) takes a form

$$\hat{V}_{\rm loss} = \int_{\hat{S}} \left[\left(\frac{\partial \hat{V}}{\partial \hat{x}}\right)^2 + \left(\frac{\partial \hat{V}}{\partial \hat{y}}\right)^2\right] {\rm d}\hat{S} \tag{20}$$

2.6. Voltage of bipolar plate between two ideally humidified hydrogen cells

To illustrate the capabilities of this approach consider local current $\tilde{j}_\lambda(\tilde{z})$ in the single-channel hydrogen cell with the ideally humidified membrane [6,7]

$$\tilde{j}_\lambda(\tilde{z}) = f_\lambda \left(1 - \frac{1}{\lambda}\right)^{\tilde{z}}, \tag{21}$$

where

$$f_\lambda = -\lambda \ln\left(1 - \frac{1}{\lambda}\right) \tag{22}$$

and λ is the oxygen stoichiometry. It is easy to verify that $\int_0^1 \tilde{j}_\lambda\,{\rm d}\tilde{z} = 1$.

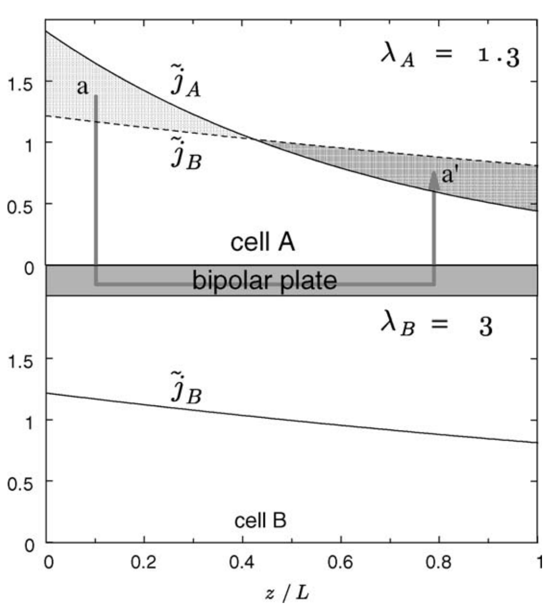

Fig. 4. Local current densities in two hydrogen cells with ideally humidified membranes running under oxygen stoichiometries $\lambda_{\rm A} = 1.3$ and $\lambda_{\rm B} = 3$. To reach load current $\tilde{j}_{\rm B} - \tilde{j}_{\rm A}$ must be transported from zone a to zone a' through the bipolar plate (thick grey arrow).

Let the cells A and B in our quasi-1D stack operate at $\lambda_{\rm A}$ and $\lambda_{\rm B}$, respectively (Fig. 4). Let the inlets of all channels be located at $z = 0$ and the outlets at $z = L$. The local currents in these cells then are $\tilde{j}_{\rm A} = \tilde{j}_{\lambda_{\rm A}}$ and $\tilde{j}_{\rm B} = \tilde{j}_{\lambda_{\rm B}}$. Note that this problem cannot be solved using simple geometrical arguments, since $\tilde{j}_{\rm A} - \tilde{j}_{\rm B}$ is not an odd function (Fig. 4).

Using $\tilde{j}_{\lambda_{\rm A}}$ and $\tilde{j}_{\lambda_{\rm B}}$ (21) in Eq. (11) and solving we find

$$\tilde{V}(\tilde{z}) = \frac{\lambda_{\rm A}}{\ln(1-(1/\lambda_{\rm A}))}\left[\left(1 - \frac{1}{\lambda_{\rm A}}\right)^{\tilde{z}} - 1\right] - \frac{\lambda_{\rm B}}{\ln(1-(1/\lambda_{\rm B}))}\left[\left(1 - \frac{1}{\lambda_{\rm B}}\right)^{\tilde{z}} - 1\right] + (\lambda_{\rm B} - \lambda_{\rm A})\tilde{z} \tag{23}$$

Voltage loss due to in-plane current in the plate is given by Eq. (18). The difference $\lambda_{\rm A} - \lambda_{\rm B}$ in the stack is usually small; let $\lambda_{\rm B} = \lambda$ and $\lambda_{\rm A} = \lambda + \delta\lambda$. Calculating integral (18) with $\tilde{V}$ (23), substituting $\lambda_{\rm B} = \lambda$ and $\lambda_{\rm A} = \lambda + \delta\lambda$ into the result and expanding over $\delta\lambda$ we find

$$\tilde{V}_{\rm loss} \simeq \left[1 + \frac{6\lambda(1-\lambda) + (1-2\lambda)/\ln(1-1/\lambda)}{4(\lambda-1)^2 f_\lambda^2}\right](\delta\lambda)^2 \tag{24}$$

where f_λ is given by (22).

The function in the square brackets in (24) is shown in Fig. 5. Under fixed $\delta\lambda$ the voltage loss dramatically increases when λ tends to 1. Note that depending on the feeding scheme the cells in a stack may operate at different stoichiometries. Typically, the cells located far from the oxygen inlet operate at lower stoichiometries than those at the inlet. Eq. (24) shows that the voltage loss in the BP between these “remote” cells may be significant. Two cells running at different stoichiometries close to 1 form a “bottleneck” for current transport through the stack; this bottleneck may reduce the overall stack efficiency. Note also that the voltage loss is proportional to the square of $\delta\lambda$; it is thus important to keep a variation of λ between two adjacent cells as small as possible.

With $\lambda = 1.1$ and $\delta\lambda = 0.2$ Eq. (24) gives $\tilde{V}_{\rm loss} \simeq 1.7 \times 10^{-2}$. The conductivity of carbon BPs σ varies between $10^2\,\Omega^{-1}\,{\rm cm}^{-1}$ [8] and $10^3\,\Omega^{-1}\,{\rm cm}^{-1}$ [9] . Taking $\sigma =$

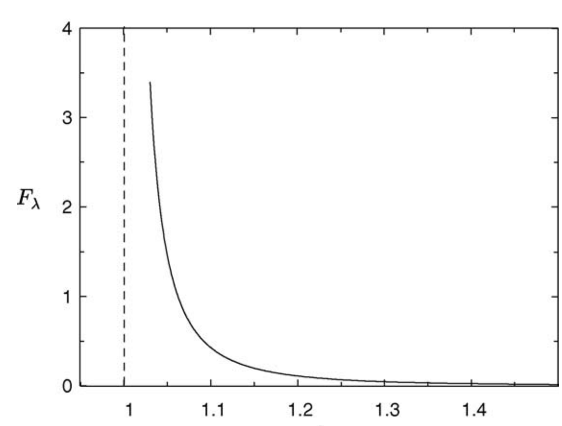

Fig. 5. The function F_λ in square brackets in (24).

$10^2\,\Omega^{-1}\,\mathrm{cm}^{-1}$, $L = 10\,\mathrm{cm}$, $h_\mathrm{p} = 0.1\,\mathrm{cm}$ and $J = 1\,\mathrm{A\,cm}^{-2}$, we get $V_\mathrm{loss} \simeq 140\,\mathrm{mV}$. This value is quite significant for fuel cell applications.

It should be emphasized that Eq. (21) is valid when the polarization voltage of the cathode side η is constant along $\tilde{z}$. Voltage drop along the bipolar plate may violate this condition. A rigorous approach requires to consider the problems in the bipolar plate and in the MEA simultaneously. The results of this work will be published elsewhere.

3. Conclusions

We have shown that in-plane current in the bipolar plate arises when the distributions of local current over the surfaces of adjacent cells are different. This in-plane current results in a variation of potential V along the BP surface. V satisfies Poisson equation; the right side of this equation is proportional to the difference of local current densities in the adjacent cells. Analytical solution to the problem is obtained for the BP separating two ideally humidified hydrogen cells running at different oxygen stoichiometries. This solution shows that the voltage loss in the BP dramatically increases when oxygen stoichiometries in both cells are different and close to 1. The general relation for the voltage loss in the bipolar plate is derived.

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