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Cell constant analytical study of electrochemical flow cell with interdigitated microelectrodes

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Abstract. This paper presents the results of investigating the influence of design parameters of an electrochemical flow cell based on film interdigitated microelectrodes on its cell constant. This investigation is performed by the analytical method. To determine the cell constant the linear resistance between the adjacent fingers of the interdigitated microelectrodes is used. In its turn this resistance is found from the potential distribution in the unit subdomain of the interdigitated microelectrode system of the cell with the limited height. The dependencies of the cell constant on the cell height and the design parameters of the interdigitated microelectrode system (the spacing between fingers and the finger width) are determined. The cell height at which the change of the design parameters of the interdigitated microelectrode system has the least effect on the cell constant is found.
Keywords: impedance measurement, electrochemical flow cell, interdigitated microelectrode system, cell constant

1. Introduction

Impedance measurement is one of promising methods for investigating various substances in chemical, biochemical and biological fields [1-2]. One of the advantages of this method is the ability to study small volumes of liquid substances. For this purpose, special electrochemical cells with various microelectrode systems are used. These cells can be either of a conventional type, designed for the study of a certain amount of a substance, or of a flow-through type, used in microfluidic analytical systems. Most often, film interdigitated microelectrodes (IDME) [3-5] are used as a system of microelectrodes in such cells. Important factors influencing on the results of the studies when using such an electrochemical cell are the geometry of the cell itself and the geometry of the electrode systems used. These factors are taken into account with the help of a cell constant [6-11]. For the cells with IDME it is difficult to determine a cell constant due to the complex geometry of the electrodes and their location on one plane of the substrate. In addition, for cells used to study small volumes of substances, the value of the cell constant depends on its size. The experimental determination of the cell constant by using the saline concentration measurement can be used only the concrete cell and does not allows one to evaluate the influence of the dimensions of a cell and a geometry of IDME on the cell constant.

The present paper is aimed to study the influence of the dimensions of a cell and a geometry of IDME on the cell constant. This investigation is based on the analytical method proposed for the analysis of electrophysical processes in the system of interdigitated microelectrodes [12].

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2. Analytical approach to study cell constant

The cell constant characterizes the geometry of the electrochemical cell and relates its measured impedance and the main electrophysical parameters of the investigated substance as conductivity and dielectric permeability

$$K_c = Z_c(\sigma + j\omega\varepsilon_0\varepsilon_r), \quad (1)$$

where K_c is the cell constant; Z_c is the cell impedance; ω is the frequency; ε_0 is the dielectric constant; σ and ε_r are the conductivity and the relative dielectric permeability of the substance, respectively.

When using a measurement on direct current the cell constant is equal to the ratio of the resistance of the electrochemical cell to the resistivity of the substance

$$K_c = R_c\sigma = \frac{R_c}{\rho}, \quad (2)$$

where R_c is the resistance of the electrochemical cell; ρ is the resistivity of the substance.

As follows from (2) to analytically find the cell constant values it is necessary to determine the resistance of the electrochemical cell at a given value of the specific conductivity of the material under study. For this purpose, we will consider the electrochemical cell with the film interdigitated microelectrodes. The structure of the cell is shown in figure 1. Because of the planar disposition of the interdigitated microelectrode system, the electrical field of the cell is non-homogeneous. The cell resistance at the direct current can be presented as follows

$$R_c = \frac{R_{id}}{L_f(2N-1)}, \quad (3)$$

where R_{id} is the linear resistance between the adjacent fingers of the interdigitated microelectrode system; L_f is the microelectrode finger length; N is the number of the fingers in each microelectrode.

To determine the linear resistance between the adjacent fingers of the interdigitated microelectrodes it is necessary to know the potential distribution between them with taking into account the dimensions of the cell itself, in particular its height. The method for determining the potential distribution in the unit subdomain of the interdigitated microelectrode system of the cell with the limited height was described in [12]. The indicated subdomain of the cell is shown in figure 1c. Using the above-mentioned method we can determine the potential distribution in the three rectangular regions of the unit subdomain (regions with the electrodes and region between them) and the current density distribution on the right and left electrodes. The 2D rectangular regions have the following dimensions

– region with the left electrode – length: $l_l = b/2$; width: $b_l = h$;

– region between the electrodes – length: $l_b = a$; width: $b_b = h$;

– region with the right electrode – length: $l_r = b/2$; width: $b_r = h$,

where b_f is the microelectrode finger width; a is the spacing between the adjacent fingers of the interdigitated microelectrodes; h is the electrochemical cell height.

According to the analytical method [12] the potential distribution in the regions is (e.g. region with the left electrode)

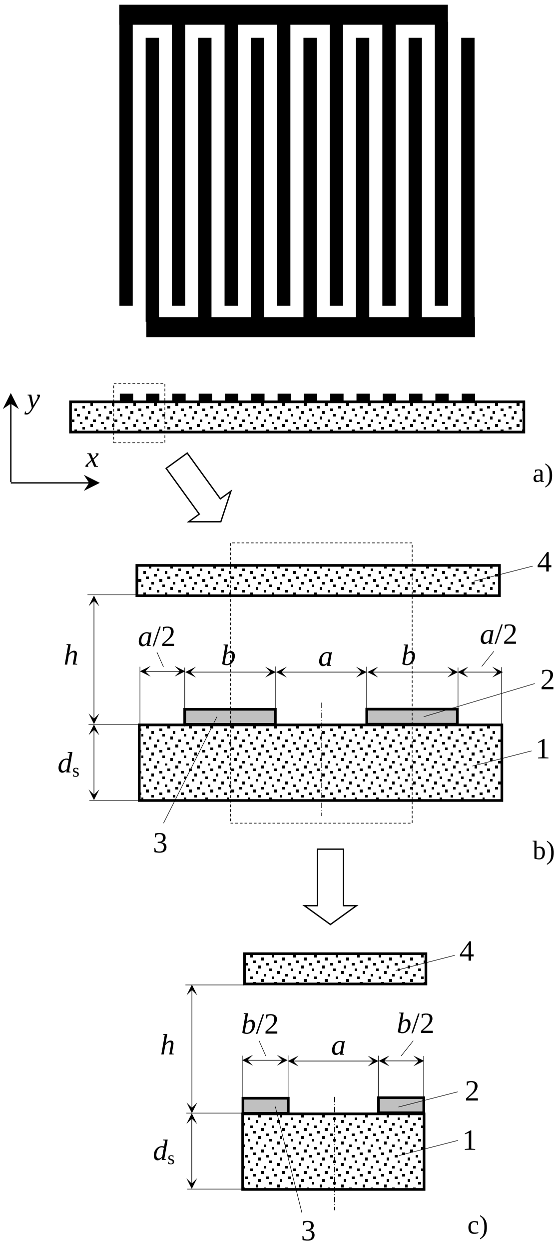

Figure 1. System of the interdigitated microelectrodes: (a) general view; (b) cross view of two adjacent fingers with an unit subdomain; (c) cross view of the unit subdomain; 1 – substrate; 2, 3 – microelectrodes; 4 – microchannel upper wall.

$$\varphi_1 = \frac{2}{bh\sigma}\left[-\delta_0^{(l,b)} + \delta_0^{(le)}\right] + \frac{4}{bh\sigma}\sum_{k=1}^{\infty}\left[-(-1)^k \delta_0^{(l,b)} + \delta_{\mathrm{k}}^{(le)}\right]\frac{1}{(2k\pi/b)^2}\cos\left(\frac{2k\pi x_1}{b}\right) +$$
$$+\frac{4}{bh\sigma}\sum_{m=1}^{\infty}\left[-\delta_m^{(l,b)} + \delta_0^{(le)}\right]\frac{1}{(m\pi/h)^2}\cos\left(\frac{m\pi y_1}{h}\right) + \frac{8}{bh\sigma}\sum_{k=1}^{\infty}\sum_{m=1}^{\infty}\left[-(-1)^k \delta_m^{(l,b)} + \delta_k^{(le)}\right]\cdot \tag{4}$$
$$\cdot\frac{1}{(2k\pi/b)^2 + (m\pi/h)^2}\cos\left(\frac{2k\pi x_1}{b}\right)\cos\left(\frac{m\pi y_1}{h}\right),$$

where φ_1 is the potential distribution in the left region; x_1 and y_1 are the coordinates of the left region; k and m are the summation indices for x and y coordinates, respectively; $\delta_m^{(l,b)}$ and $\delta_k^{(le)}$ are the weighting coefficients which determine the current densities on the following boundaries of the left region: the boundary with the region between the electrodes and the boundary with the left electrode, respectively.

The current density on the electrodes can be determined using the expression for the potential distribution in the regions with electrodes (e.g. region with the left electrode)

$$j_{\mathrm{le}} = -\sigma \frac{\partial \varphi_1}{\partial y_1}, \tag{5}$$

where j_{le} is the current density on the left electrode.

Using (4) and (5) we obtain the expression for the linear current through left electrode.

$$I_{\mathrm{le}} = \int_0^{b/2} j_{\mathrm{le}} \partial x_1 = \delta_0^{(le)}, \tag{6}$$

where I_{le} is the linear current through the left electrode.

Knowing the linear current through one of the electrodes (e.g. left electrode) one can determine the linear resistance between the adjacent fingers of the interdigitated microelectrodes

$$R_{\mathrm{id}} = \frac{\varphi_{\mathrm{le}} - \varphi_{\mathrm{re}}}{I_{\mathrm{le}}}, \tag{7}$$

where φ_{le} and φ_{re} is the potential of the left and right electrodes, respectively.

Using (3) and (7) in (2) one can analytically investigate the influence of the electrochemical cell height and the interdigitated microelectrodes geometry on the cell constant.

3. Results and discussion

All the analytical studies of the cell constant have been performed for the electrochemical cell with the interdigitated microelectrodes having the following design parameters the values of which presented in table 1.

Table 1. Design parameter of the electrochemical cell

Parameter	Variation	Value
Cell height, mm	yes	0.25 – 15.0
Number of fingers	no	25
Finger length, mm	no	10.0
Finger width, mm	yes	0.1 – 1.0
Spacing between fingers, mm	yes	0.1 – 1.0
Conductivity of substance, Sm/m	no	$1.0 \cdot 10^{-4}$
Voltage between electrodes, V	no	4.0

The dependences of the cell constant of the electrochemical flow cell on its height for the various values of the design parameters of the interdigitated microelectrode system (the spacing between fingers and the finger width) are shown in figure 2. The presented dependences indicate that with increasing the cell height the cell constant decreases regardless of the spacing between fingers and their width. These dependences have the two sections with the various slopes. For the small cell height (up to 0.5 mm) dependences of the cell constant on the cell height are characterized by the strong slope. This slope is greater, the greater the spacing between fingers and the finger width in the interdigitated microelectrode system. The gentle slope of the dependences begins at approximately the cell height of 0.5 mm and continues up to 15 mm. In this section, on the contrary, the greatest slope is observed in the system of the interdigitated microelectrodes with the smallest spacing and the smallest width of the fingers.

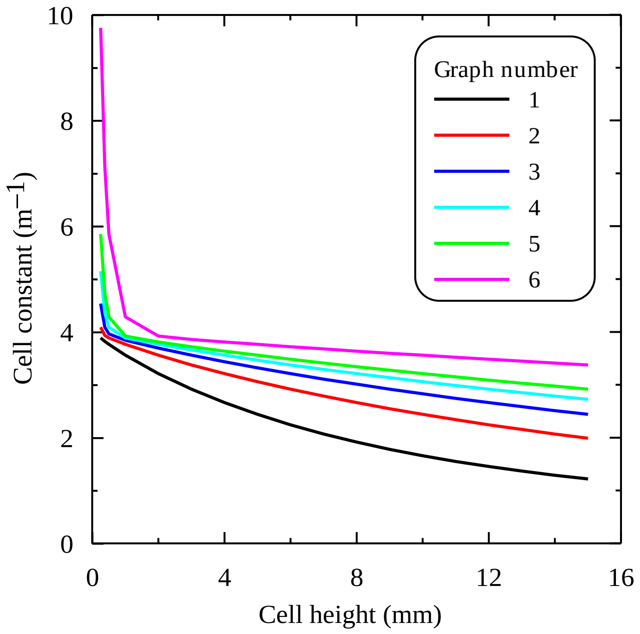

Figure 2. Dependences of the cell constant of the electrochemical flow cell on its height for the following values of the design parameters of the interdigitated microelectrode system (the spacing between fingers (a) and the finger width (b) (a=b)): 1 – 0.1 mm; 2 – 0.2 mm; 3 – 0.3 mm; 4 – 0.4 mm; 5 – 0.5 mm; 6 – 1.0 mm.

The dependences of the cell constant of the electrochemical flow cell on the spacing between fingers and the finger width in the system of the interdigitated microelectrodes for various values of the cell height are shown in figure 3. As it can be seen, with increasing the spacing between fingers and the finger width the value of the cell constant increases. However this increase has the different character depending on the cell height. For the cells with the small height (up to 0.5 mm), the largest increase of the cell constant with increasing the spacing between fingers and the finger width is observed at large values of these parameters (from 0.3 to 1.0 mm). For the cells whose heights are 1-2 mm the modest increase is observed for the all range of the spacing between fingers and the finger width. Finally, at large values of the cell height (more than 2 mm), we observe a significant increase in the cell constant at small values of the spacing between fingers and the finger width.

The presented dependences in figure 3 show that at the certain values of the cell height, the cell constant weakly depends on the design parameters of the interdigitated microelectrode system. Since the all dependences of the cell constant on the design parameters of the interdigitated microelectrode system are monotonically increasing functions (see figure 3), their slope can be characterized by the ratio between the cell constant at the maximum values of the design parameters of the interdigitated microelectrode system and the cell constant at the minimum values of these parameters. The dependence of this ratio on the cell height allows one to determine the cell height at which the change of the design parameters of the interdigitated microelectrode system has the least effect on the cell constant. The given dependence is presented in figure 4. As it can be seen from this dependence the minimum ratio of the cell constant at the maximum values of the design parameters of the interdigitated microelectrode system to the cell constant at the minimum values of these parameters is observed in the cell with the height equal to 1.0 mm.

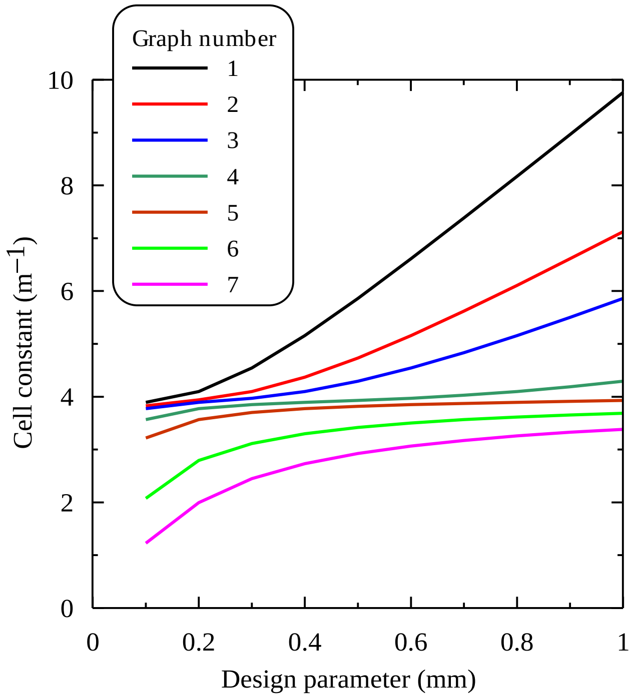

Figure 3. Dependences of the cell constant of the electrochemical flow cell on the design parameters of the interdigitated microelectrode system (the spacing between finger (a) and the finger width (b) (a=b)) for various values of the cell height: 1 – 0.25 mm; 2 – 0.375 mm; 3 – 0.5 mm; 4 – 1.0 mm; 5 – 2.0 mm; 6 – 7.0 mm; 7 – 15.0 mm.

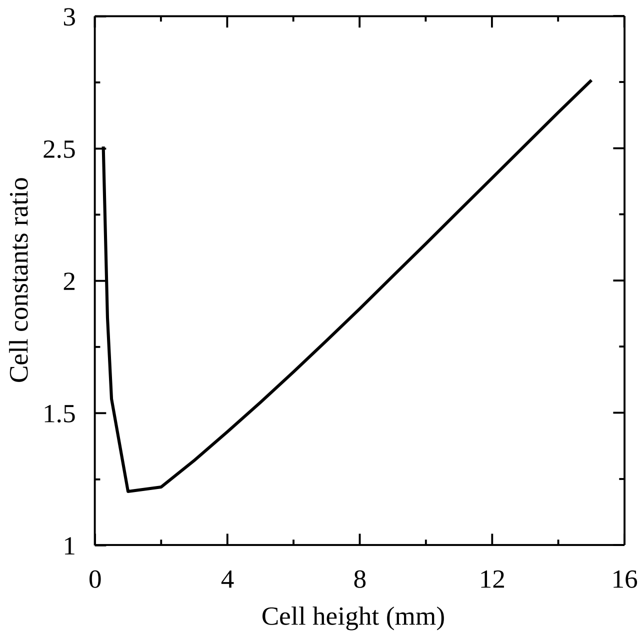

Figure 4. Ratio between the cell constants at the maximum and minimum values of the design parameters of the interdigitated microelectrode system as a function of the cell height.

4. Conclusion

In this paper, the influence of the design parameters of the electrochemical flow cell based on the film interdigitated microelectrodes on its cell constant was investigated with using the analytical method. It was found that the cell constant decreases with increasing the cell height and increases with increasing the values of the design parameters of the interdigitated microelectrode system: the spacing between fingers and the finger width. It was also found that at the certain cell height, the weak dependence of the cell constant on the design parameters of the interdigitated microelectrode system is observed. The presented results can be used to create electrochemical flow cells with the low sensitivity to errors of design parameters.

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