

DATA FUSION FOR CHEMFET-BASED MEASUREMENTS

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ABSTRACT: Arrays of CHEMFET sensors can potentially increase measurement accuracy and range of operation as compared to usage of stand-alone sensors. To benefit the synergistic effect of the sensor array one needs accurate models and appropriate data processing techniques. This paper presents a mathematical formulation of one-sensor and multiple-sensor CHEMFET-based measurement problems and discusses its numerical properties. The main contribution is estimation of accuracy limits, for both one- as well as for multiple-sensor measurements, using two representative CHEMFET sensor models – the well-known semi-empirical Nikolsky-Eisenmann (NE) model, and a recently developed physics-based Reduced-Super-Nikolsky (RSN) model.

INTRODUCTION

CHEMFET sensors are important devices in the area of on-line monitoring of ions in water solutions [12]. Their typical responses to variable activity of main ions, for constant activities of interfering ions, are shown in fig. 1.

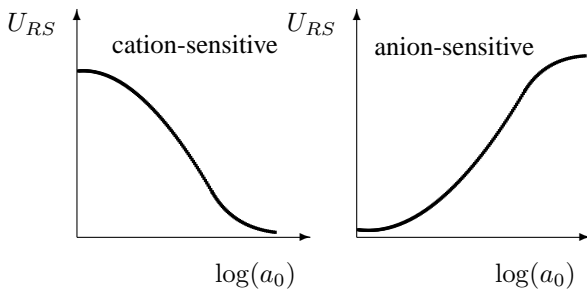


Fig. 1. Typical voltage responses U_{RS} of cation and anion sensitive CHEMFET sensors for constant activities of interfering ions and variable activity of the main ion a_0

Useful operation range of cation (anion) selective sensor is limited on the side of high ionic activities a_m of the main ion (i.e. the ion the sensor is designed to be most sensitive to) by influence of counter-ions, i.e. ions with opposite sign of charge. Practically more important is saturation of the response for low activities of the main ion, caused by interfering ions of the same sign of charge. Sensor selectivity is a measure of the relative strength of influence upon response of a given ion w.r.t. the main ion. For an ideal sensor the sensitivity coefficient is 0 for all interfering ions, and so knowing sensor output it is possible to directly find the main ion activity – just using the inverse response curve for the given calibrated sensor. For non-ideal, i.e. real life, sensors the mapping between sensor output and the main ion activity is not unique, because it depends on unknown (since uncontrolled and unmeasured) activities of other ions in the solution under test. Finite selectivity thus causes measurement error. Reduction of this error is possible when all major ions

are measured by separate sensors (and selectivities of all sensors to all ions are available from sensor calibration) – e.g. using the data fusion techniques [6, 1].

Benefits of such accuracy boosting techniques are available only when sufficiently accurate models of the actual sensor devices are available, and sensor does not change its properties in time. This paper discusses formulation and properties of the one-sensor and multi-sensor measurement problem for two representative CHEMFET sensor models. However, it is not the author's intent to evaluate accuracy of any sensor model, i.e. to compare model predictions with measurements, but only to present consequences of the selection for the numerical data processing of raw sensor responses.

MEASUREMENT PROBLEM

CHEMFET-based measurement requires availability of a generic relationship between activity a_0 of a ion of interest in the electrolyte under test and the sensor output signal (here: the output voltage, denoted with U_{RS}). The relationship $a_0 \rightarrow U_{RS}$ is in fact parametrised with operating point, temperature and technological details of sensor design and manufacturing. To use a particular sensor device for measurement at a fixed temperature and operating point – calibration is needed, to resolve ambiguity of the $a_0 \rightarrow U_{RS}$ mapping, that is related to sensor design and manufacturing. After calibration the mapping should be 1:1 and easy invertible, so that having U_{RS} it is possible to determine (uniquely, accurately and fast) the unknown ion activity a_0 . In real life CHEMFET sensors are not ideally specific, as their output signal depends on more than one ion, and neglecting their interference can cause inaccuracy of the measurement. This section discusses specifics of CHEMFET-based sensing: modelling, calibration and estimation of ionic activities from CHEMFET output signals using one-sensor measurements and sensor array measurements with data fu-

sion (DF) type of raw measurement processing.

Data fusion term is used here as a generic name for data processing procedures that combine information from several sensors of limited selectivity so as to improve on resulting measurement accuracy.

Modelling For Data Fusion

In this paper modelling of CHEMFET sensor assumes separability of CHEMFET model – as shown in fig. 2.

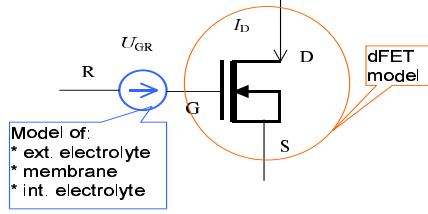


Fig. 2. A separable CHEMFET model

The electro-chemical transducer – formed with the reference electrode (R), the electrolyte, the ion-selective membrane and FET gate insulator is represented with a voltage source, dependent on ionic activities and temperature. The other component is a gateless (usually depleted type) MOS transistor structure, which has its channel conductivity modulated with changes of ionic charge in the ion-selective membrane. Properties of the internal transistor structure is important when considering rational selection of the operating point, i.e. values of the drain current I_D and the drain to source voltage U_{DS} (see [7, 8]). However, in standard measurement mode the operating point of the FET structure is kept constant. In effect FET properties are of secondary importance for the CHEMFET operation and so will not be discussed in details here. That way modelling effort is concentrated at the transducing part of CHEMFET sensor. Two types of models are considered: the well-established Nikolsky-Eisenmann model (NE, [2]), and a relatively new model called here the Reduced-Super-Nikolsky model (RSN, [4, 5]). They both neglect influence of counter-ions, which is acceptable for good quality sensors and water monitoring and simplifies sensor characterisation and calibration.

Nikolsky-Eisenmann (NE) model. Let us assume a constant operating point (I_D , U_{DS}) and electrolyte with m ions, activities a_0, \dots, a_{m-1} and valencies z_0, \dots, z_{m-1} (of the same sign). The output sensor voltage U_{RS} can be expressed as:

$$U_{RS} = U_0 - N \frac{V_T}{z_0} \ln \left(a_0 + \sum_{j=1}^{m-1} K_{j,0} \cdot a_j^{z_0/z_j} \right) \quad (1)$$

$K_{j,0}$ are selectivity coefficients of the j -th ion w.r.t. the main one (index 0), $V_T = kT/q$, N is a nonideality coefficient and U_0 – the offset voltage. The model allows for *explicit* calculation (prediction) of CHEMFET output voltage U_{RS} for a given ionic content. Calculation of the

main ion activity a_0 , given sensor output voltage U_{RS} and activities of the interfering ions a_1, \dots, a_{m-1} is *explicit* as well, as:

$$a_0 = e_B^{-z_0} - \sum_{j=1}^{m-1} K_{j,0} \cdot a_j^{z_0/z_j}, \quad (2)$$

$$\text{where } e_B = \exp \left(\frac{U_{RS} - U_0}{NV_T} \right)$$

Fig. 3 depicts response curves calculated from the NE model for two cases: a) $z_0 = z_1 = 1$, b) $z_0 = 1, z_1 = 2$. Saturation of the sensor curve is more profound in the second case, where the interferent has larger valency than the main ion.

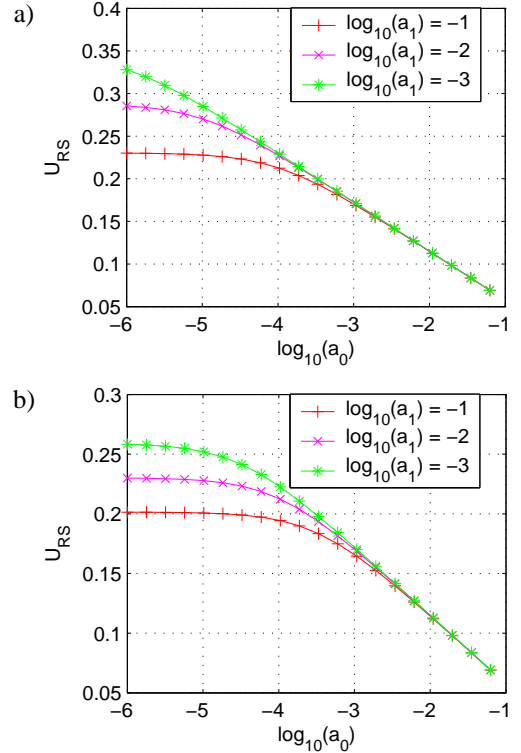


Fig. 3. Dependence of NE modelled sensor response curve on interfering ion activity for $K_{1,0} = 0.001$ and: a) $z_0 = z_1 = 1$, b) $z_0 = 1, z_1 = 2$.

Reduced-Super-Nikolsky (RSN) model. The RSN model [4, 5] *implicitly* relates the U_{RS} voltage to the ionic activities:

$$1 = a_0 \cdot \tilde{e}_B^{z_0} + \sum_{j=1}^{m-1} \tilde{K}_{j,0} \cdot a_j \cdot \tilde{e}_B^{z_j}, \quad (3)$$

$$\text{where } \tilde{e}_B = \exp \left(\frac{U_{RS} - \tilde{U}_0}{\tilde{N}V_T} \right)$$

Tilde over symbols differentiates parameters of RSN from parameters of the NE model. For fixed temperature the two models require the same number of $m + 1$ coefficients (to be determined in the course of a sensor calibration process).

Calculation of the main ion activity a_0 , given the sensor output voltage U_{RS} and activities of the interfering ions

a_1, \dots, a_{m-1} is *explicit* as well:

$$a_0 = \tilde{e}_B^{-z_0} \left(1 - \sum_{j=1}^{m-1} \tilde{K}_{j,0} \cdot a_j \cdot \tilde{e}_B^{z_j} \right) \quad (4)$$

One can see, that (2) and (4) have identical form for $z_0 = z_1 = \dots = z_{m-1}$, but they differ for different valencies in the way they represent contribution of interfering ions.

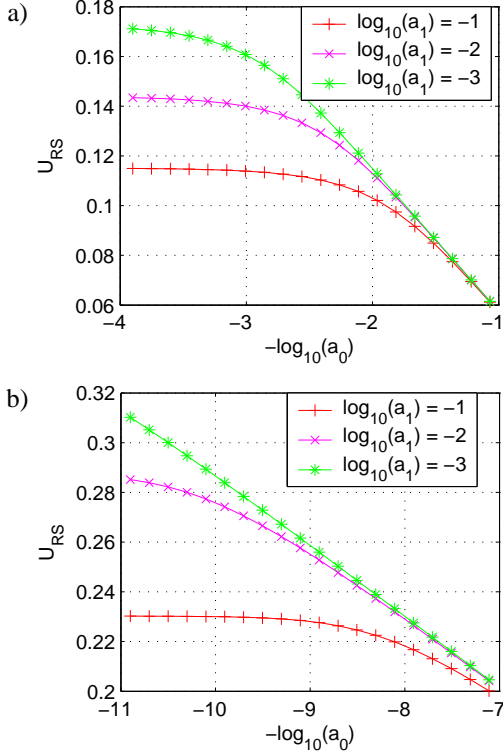


Fig. 4. Dependence of RSN modelled sensor response curve on interfering ion activity for $K_{1,0} = 0.001$ and: a) $z_0 = 1, z_1 = 2$, b) $z_0 = 2, z_1 = 1$.

Fig. 4 depicts response curves calculated from the RSN model for two cases: a) $z_0 = 1, z_1 = 2$, b) $z_0 = 2, z_1 = 1$. Saturation of the sensor curve is more profound in the first case, where the interferent has larger valency than the main ion (similarly as predicted by the NE model).

Model Calibration

Let us now assume that we have n measurements $U^{(i)}$ of sensor voltage (U_{RS}), corresponding to N sets of ionic activities $\mathbf{a}^{(i)} = [a_0^{(i)}, a_1^{(i)}, \dots, a_{m-1}^{(i)}]$, $i = 1, \dots, N$. Let us also denote responses of a corresponding sensor model with:

$$\tilde{U}^{(i)}(\mathbf{p}) = \tilde{f}(\mathbf{a}^{(i)}, \mathbf{p}) \quad (5)$$

where \mathbf{p} stands for a vector of model parameters to be determined via calibration procedure, e.g. for the NE model $\mathbf{p} = [U_0, N, K_{1,0}, \dots, K_{m-1,0}]$. There are two components of any calibration:

- selection of a calibration plan, i.e. the number of calibration experiments n and values of activities $\mathbf{a}^{(i)}$ for each experiment

- fitting model to measurements by adjustment of parameters \mathbf{p} .

Let us denote with \underline{a}_j and \bar{a}_j the minimum and maximum activities of interest for the j -th ion. The following minimal experiment plan with $N = m + 1$ can be used:

1. Measure $U^{(1)}$ for $\mathbf{a}^1 = [\underline{a}_0, \dots, \underline{a}_{m-1}]$
2. For $k = 2, \dots, m + 1$ measure $U^{(k)}$ for $\mathbf{a}^{(k)} = [\underline{a}_0, \dots, \underline{a}_{k-3}, \bar{a}_{k-2}, \underline{a}_{k-1}, \dots, \underline{a}_{m-1}]$

Let us denote with $r_i, i = 1, \dots, N$ the following relative-absolute error measure of a difference between model $\tilde{U}^{(i)}$ and respective measurement $U^{(i)}$ values:

$$r_i(\mathbf{p}) = \frac{\tilde{U}^{(i)}(\mathbf{p}) - U^{(i)}}{\max(U)^{(i)}, \varepsilon_U}, \text{ for some } \varepsilon_U > 0 \quad (6)$$

Then fitting model to measurements can be formulated as a minimisation of a norm of $\mathbf{r}(\mathbf{p})$ w.r.t. \mathbf{p} vector, e.g.:

$$\min_{\mathbf{p} \in \mathbb{P}} F_2(\mathbf{p}) \equiv \frac{1}{2} \sum_{i=1}^N r_i^2(\mathbf{p}) \quad (7)$$

where \mathbb{P} is a feasibility set for parameter vector \mathbf{p} , e.g. $\mathbb{P} = \{\mathbf{p} \mid \underline{p}_j \leq p_j \leq \bar{p}_j, j = 1, \dots, n = m + 1\}$ (with $\underline{p}_j < \bar{p}_j$ being lower and upper bounds of parameter values).

Let us now notice the important difference between the two CHEMFET models considered here. In the NE model the response voltage is an *explicit* function of ion activities (1), i.e. the error functions $r_i(\mathbf{p})$ are explicit functions as well. For the RSN model the same relationship is generally *implicit*. Fortunately, the RSN model equation (3) can be converted to a polynomial equation of degree $d = \max(|z_0|, |z_1 - z_0|, \dots, |z_{m-1} - z_0|)$ w.r.t. \tilde{e}_B . Most practical cases of interest satisfy condition $d \leq 4$, and then roots of the equation have *explicit* formulae, yet different for different d ¹. In general the RSN model has to be solved iteratively, to determine for given activities the corresponding value of model output voltage (5). Since iterative calculations reduce accuracy – one might consider the least squares solution of the n RSN equations (3) instead of fitting the implicitly defined sensor response curve (5). This means replacement of $r_i(\mathbf{p})$ in (7) with the following expression:

$$r_i(\mathbf{p}) = \tilde{e}_B^{z_0} a_0^{(i)} + \sum_{j=1}^{m-1} \tilde{K}_{j,0} \cdot a_j^{(i)} \cdot \tilde{e}_B^{z_j} - 1 \quad (8)$$

Yet another possibility is fitting inverse response curves $a_0(U_{RS}, a_1, \dots, a_{m-1})$ expressed with (2), (4). For the RSN model this leads to:

$$r_i(\mathbf{p}) = r_{i,0} + z_0 \frac{U^{(i)} - \tilde{U}_0}{\tilde{N} V_T} \ln \left(1 - \sum_{j=1}^{m-1} \tilde{K}_{j,0} \cdot a_j \cdot \tilde{e}_B^{z_j} \right) \quad (9)$$

¹Inherent to modelling sensor response for different valencies of ions is a problem of multiplicity of solution candidates due to nonlinearity of modelling equations for both NE (powers of activities) and RSN models (powers of e_B). Fortunately, proper solutions can be found by applying physics-based root selection rules.

where $r_{i,0} = \ln(a_0^{(i)})$. For the NE model one would have:

$$r_i(\mathbf{p}) = r_{i,0} + z_0 \frac{U^{(i)} - \tilde{U}_0}{\tilde{N}V_T} \ln\left(1 - \sum_{j=1}^{m-1} K_{j,0} \cdot a_j^{z_0/z_j} e_B^{z_0}\right) \quad (10)$$

For minimum cardinality N of the experiment plan (when N is equal to the number of model parameters $n = m+1$) all three formulations are equivalent – assuming exact calculations. Otherwise, numerical results differ and selection of the best fitting criterion arises. It has been numerically verified, that accuracy of the calibration is determined mainly by ability of a model to represent real CHEMFET response, and little by selection of fitting criteria or optimisation accuracy.

Single Versus Multiple Sensor Measurements

After calibration the following relationship between m ionic activities \mathbf{a} and the i -th sensor model output voltage $\tilde{U}_{RS}^{(i)}$ is available (for fixed environmental parameters, such as temperature):

$$\tilde{U}_{RS}^{(i)} = \hat{f}_i(\mathbf{a}) \equiv \tilde{f}_i(\mathbf{a}, \hat{\mathbf{p}}^{(i)}) \quad (11)$$

for $n = m + 1$ element wektor $\hat{\mathbf{p}}^{(i)}$ of NE/RSN model parameters. Since (11) defines m to 1 mapping – it cannot be inverted w.r.t. some component of \mathbf{a} , for example a_i . To be able to measure with a single sensor one *has to know or assume* values of other ion activities. In case of zero knowledge of ionic content – zero values of unknown a_j , $j \neq i$ are typically used.

In the basic DF approach there are simultaneous measurements $U_{RS}^{(i)}$, $i = 1, \dots, m$ made with m different calibrated sensors. Algebraically, there are m equations (11) with m unknowns a_0, \dots, a_{m-1} ; in vector notation:

$$\tilde{\mathbf{U}}_{RS} = \hat{\mathbf{f}}(\mathbf{a}) \quad (12)$$

The set of equations implicitly defines inverse mapping $\tilde{\mathbf{U}}_{RS} \rightarrow \mathbf{a}$ unambiguously (if the m equations are independent). Mathematically such a calculation belongs to a class of inverse problems, as *the basic modelling problem* is a calculation of the output sensor voltages – given the ion activities and model parameter values (11).

For the NE model the basic modelling problem is non-linear (w.r.t activities), and so non-linear is the inverse problem. Rearranging (2) and adding i index to denote the i -th sensor the inverse problem can be written as a set of equations that are *non-linear* w.r.t. unknown ion activities $a_{0,i}, \dots, a_{m-1,i}$:

$$a_{0,i} + \sum_{j=1}^{m-1} K_{j,0,i} a_{j,i}^{z_0/z_{j,i}} = e_{B,i}, \quad (13)$$

where $e_{B,i} = \exp(z_{0,i} \frac{U_{0,i} - U_{RS,i}}{N_i V_T})$.

Each activity in equations (13) is a component of the vector \mathbf{a} that contains activities of all measured ions, i.e.: each $a_{j,i} \in \{\mathbf{a}_1, \dots, \mathbf{a}_m\}$, with \mathbf{a}_k denoting the k -th element of \mathbf{a} .

For the RSN model the inverse problem can be written as a set of *linear* equations w.r.t. unknown ion activities $a_{0,i}, \dots, a_{m-1,i}$:

$$\tilde{e}_B^{z_0} a_{0,i} + \sum_{j=1}^{m-1} \tilde{K}_{j,0,i} \cdot a_{j,i} \cdot \tilde{e}_B^{z_{j,i}} = 1 \quad (14)$$

where $\tilde{e}_{B,l} = \exp(z_{0,l} \frac{U_{0,l} - U_{RS,l}}{N_l V_T})$.

For solvability of each data fusion equation set (i.e. (13), (14)) there are at least m independent equations needed. Since for performing calibration the number of sensor is at least equal to the number of parameters $n > m$, so the data fusion set of equations (12) is *overdetermined*. In such a case the solution can be found from the constrained least squares problem of the following form:

$$\min_{\mathbf{a} \in \mathcal{A}} \frac{1}{2} \sum_{n=1}^n g_n^2(\mathbf{a}) \quad (15)$$

$$g_i(\mathbf{a}) = U_{RS}^{(i)} - \hat{f}_i(\mathbf{a}) \quad (16)$$

$$\mathcal{A} = \{\mathbf{a} \mid \underline{a}_i \leq a_i \leq \bar{a}_i, i = 1, \dots, n\} \quad (17)$$

Values of \underline{a}_i , \bar{a}_i can be selected as realistic lower/upper bounds on measured ion concentration. They form safeguards against inaccuracy of calculations.

For the RSN model calculation of the error function g_i in the form (16) requires solution of a non-linear (w.r.t. unknown U_{RS}) model equation (3). To ease implementation of DF algorithms for that model another (*explicit*) form of the error function is proposed:

$$g_i(\mathbf{a}) = \tilde{e}_B^{z_0} a_{0,i} + \sum_{j=1}^{m-1} \tilde{K}_{j,0,i} \cdot a_{j,i} \cdot \tilde{e}_B^{z_{j,i}} - 1 \quad (18)$$

PROPERTIES OF THE PROBLEM

Ideally DF requires at least one sensor that is most sensitive to one of the ions in the electrolyte under test. Such a requirement is hard to satisfy – especially for field measurements. That is why it is interesting to estimate consequences of not taking into account measurement of some ions.

The limit case is just the one-sensor measurement without any knowledge of interfering ions. Let us then estimate inaccuracy of the one-sensor measurement technique in the simplest case, when two ions are to be measured. The relative difference between activity \tilde{a}_0 determined from one-sensor measurement, using the NE model, and the activity calculated using DF principles (assuming additional measurement of the activity a_1 of the only interferent, and also knowledge of accurate value of the selectivity coefficient $K \equiv K_{1,0}$) is equal to:

$$\delta[\tilde{a}_0] \equiv \frac{\tilde{a}_0 - a_0}{a_0} \approx \frac{K \cdot a_1^{z_0/z_1}}{a_0} \quad (19)$$

Fig. 5 visualises the NE model predicted dependence of one-sensor measurement inaccuracy on the main ion activity a_0 for one level of interferent activity $a_1 = 0.1 \text{ mol/l}$ and three levels of sensor selectivity K . It is seen, that

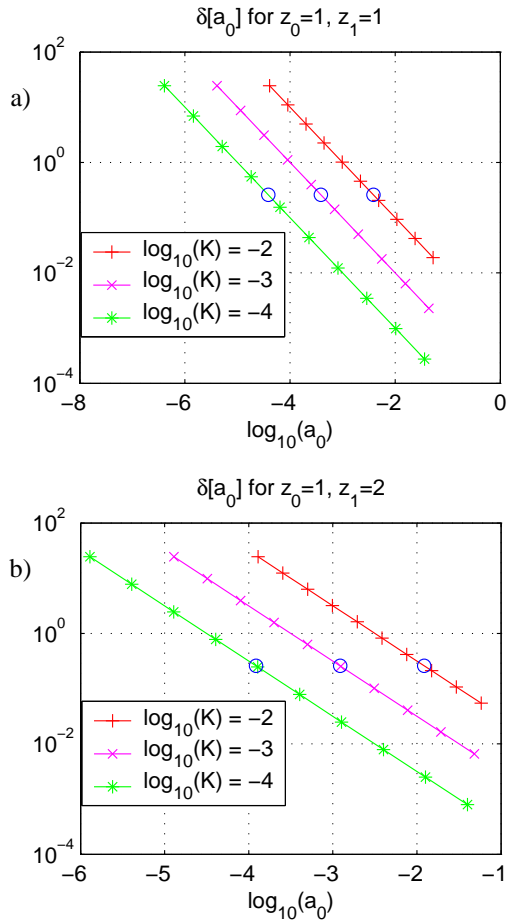


Fig. 5. NE model predicted inaccuracy of the one-sensor measurements for interfering ion activity $a_{1max} = 0.1 \text{ mol/l}$, $z_0 = 1$ and: a) $z_1 = 1$ or b) $z_1 = 2$.

accuracy loss due to using one-sensor measurement is substantial for low level of the main ion activity and high level of an interfering ion activity, especially for medium and low sensor selectivity.

Ion concentrations are typically expressed logarithmically, as $p_x = -\log(a_x)$. Relative inaccuracy of the main ion concentration $\delta[a_0]$ can be converted to absolute error of the logarithmic measures as follows:

$$\Delta p_0 \equiv \tilde{p}_0 - p_0 = -\log(\delta[a_0] + 1) \quad (20)$$

The minimum “one-sensor measured” activity (i.e. the activity for which the allowable logarithmic inaccuracy attains Δp_0) can be expressed as:

$$p_{0min} = \frac{z_0}{z_1} p_1 - \log(K_{1,0}) + \log(10^{-\Delta p_0} - 1) \quad (21)$$

$$a_{0min} = 10^{-p_{0min}}$$

Fig. 5 marks with circles these points, where the relative inaccuracy ≈ 0.259 corresponds to $\Delta p_0 = 0.1$ (this is a reasonable requirement for chemical measurement accuracy).

For the RSN model relative accuracy of one-sensor measurements cannot be expressed with such a simple to interpret formula as (19), since:

$$\delta[\tilde{a}_0] = \frac{K \cdot a_1}{a_0} \tilde{e}_B^{z_1 - z_0} \quad (22)$$

and so for $z_1 \neq z_0$ additional $\tilde{e}_B(a_0, a_1, z_0, z_1)$ term comes into play. As mentioned earlier, the equation (3) can be converted to a polynomial equation of degree d , which is typically smaller than 4; then roots of the equation have *explicit* formulae.

Since for $z_0 = z_1$ NE and RSN models are identical – two other important special cases are considered: a) $z_0 = 1$, $z_1 = 2$ and b) $z_0 = 2$, $z_1 = 1$. For the case a) the RSN model equation (3) becomes: $K a_1 \tilde{e}_B^2 + a_0 \tilde{e}_B - 1 = 0$, and so:

$$\delta[\tilde{a}_0] = \frac{\sqrt{1 + 4K a_1 / a_0^2} - 1}{2} \quad (23)$$

For the case b) we have: $a_0 \tilde{e}_B^2 + K a_1 \tilde{e}_B - 1 = 0$, hence:

$$\delta[\tilde{a}_0] = \frac{2}{\sqrt{1 + 4a_0 / K^2 / a_1^2} - 1} \quad (24)$$

If one limits the inaccuracy – values of a_{0min} (or p_{0min}) can be calculated, separately for each of the two cases.

Fig. 6 visualises RSN model predicted dependence of one-sensor measurement inaccuracy on the main ion activity a_0 for one level of interferent activity $a_1 = 0.1 \text{ mol/l}$ and three levels of sensor selectivity K – same as used in fig. 5. Circles mark these points, where the relative inaccuracy ≈ 0.259 , which corresponds to $\Delta p_0 = 0.1$. It

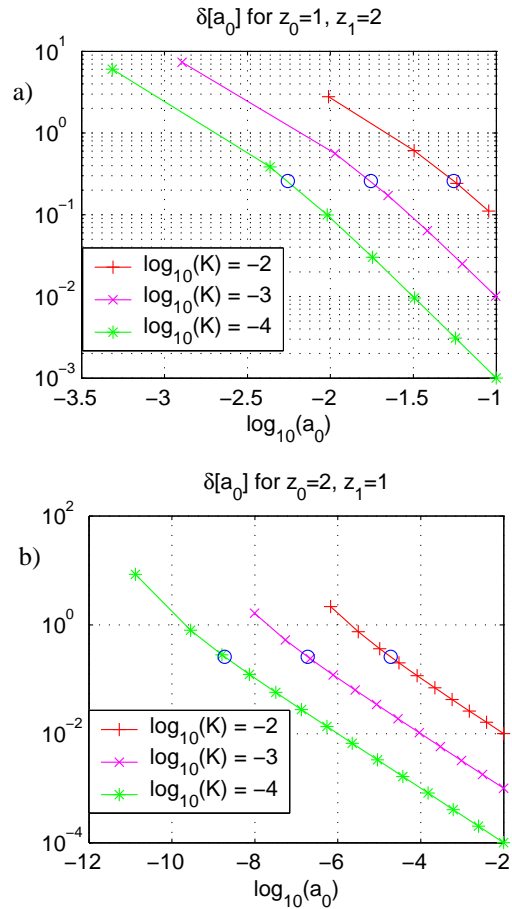


Fig. 6. RSN model predicted inaccuracy of the one-sensor measurements for interfering ion activity $a_{1max} = 0.1 \text{ mol/l}$, $z_0 = 1$ and: a) $z_1 = 1$ or b) $z_1 = 2$

is seen, that for sensors which can be modelled with the RSN model – presence of a 2-valent interfering ion in-

increases the minimum ion activity so much, that the sensor can be useless, e.g. for clean water measurements.

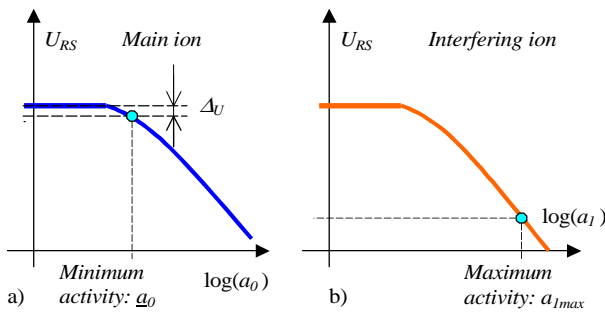


Fig. 7. Limitation of sensing range

The minimum detectable activity can be also attributed to a finite accuracy of voltmeter for U_{RS} measurements. Let us denote with Δ_U the absolute inaccuracy of voltage measurement. Saturation of the sensor response curve for low activity of the main ion (the response in fig. 7a) is pronounced most for the maximum allowable activity a_{1max} of the interfering ion (it is the main ion for a second sensor - with response in fig. 7b).

Using the NE model we can say, that activities a_0 that are smaller than:

$$\underline{a}_0 \approx K_{1,0} \cdot a_{1max}^{z_0/z_1} \cdot (\exp(\delta_U) - 1), \quad (25)$$

where $\delta_u = \left| z_0 \frac{\Delta_U}{V_T} \right|$

cannot be safely distinguished by measurements. E.g. for $\Delta_U = 1\text{mV}$, $V_T = 25\text{mV}$, equation (25) reads: $\underline{a}_0 \approx 0.04 \cdot K_{1,0} \cdot a_{1max}^{z_0/z_1}$. It turns out (also, when predicting with the RSN model), that for one-sensor measurements a_{0min} is significantly larger than \underline{a}_0 and so determines the one-sensor lowest measureable activity level. For multiple-sensor measurements a_{0min} value is meaningless. In such a case \underline{a}_0 value determines the smallest reliably measured ion activity ².

SUMMARY

The paper compares one-sensor and multiple-sensor approaches to measurement with CHEMFETs, using two principally different CHEMFET models – the well-known semi-empirical NE model, and a Van den Berg theory [11] related novel RSN model. The main contribution is estimation of accuracy limits for both one- as well as for multiple-sensor measurements. The paper formulates also two numeric tasks related to accurate measurements, i.e. calibration and data fusion in the form that is amenable to computer implementation. Main properties of the tasks are detailed for both CHEMFET models. From the numerical point of view both models lead to a *nonlinear* optimisation problem – for calibration or data fusion with any valency of ions. The RSN model leads to *linear* data fusion problem, and so it is computationally superior to the NE model – when many measure-

ments can be made (and processed) after each calibration of sensors. Details of the C-language special-purpose implementation of calibration and DF algorithms, targeted at a microprocessor controller of an automatic measurement system, will be presented in a separate paper.

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²Another approach to estimation of measurement inaccuracy due to voltmeter errors can be found in [6].