

MATHEMATICAL MODELLING OF THE PROCESSES OF COMPONENT DIFFUSION IN THE CORE–GRAPHITE ELECTRODE SYSTEM IN AN INDUSTRIAL ARC STEELMAKING DC FURNACE OF THE DSP PS-12 TYPE

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ABSTRACT

The work shows the possibility of using the method of mathematical modelling to predict the distribution of chemical components in the core-electrode system during operation in an arc steelmaking furnace, taking the diffusion processes into account. The diffusion coefficients for each component were determined on the basis of the developed two-dimensional finite element model of the process of component diffusion in this system, and taking into account the experimental data on the residual distribution of the component content in the cross-section of the cored electrode. These coefficients were used to conduct modelling of the diffusion process in order to assess the possible distribution of the component content in the cored electrodes of an increased diameter and to demonstrate the modelling results, taking into account different initial concentrations.

KEYWORDS: arc steelmaking furnaces, graphite cored electrodes, specific electrical resistance, components, concentration, diffusion, mathematical modelling

INTRODUCTION

The composition of graphite electrode cores can vary widely depending on the type of furnace, the type and quality of the charge, steel grade, electrical conditions, etc. [1, 2]. The core in the initial state consists of a mixture of graphite with impurities of components containing Li, Na, K, etc.

Optimisation of the initial chemical composition of the core for electrodes of different type size (diameter) and purpose can be performed by numerical experiments (mathematical modelling) of the process of mutual diffusion of chemical elements (components) in the core-electrode system at high temperatures in a furnace, taking into account the known data on the diffusion coefficients of these elements in graphite. However, such data, taking into account high temperatures in a furnace (1800–2300 °C) and the near-arc region of the electrode itself of up to 4000 °C, is almost not publicly available. For example, the works [3–5] present experimental data on the diffusion coefficients of some elements (Li, Na, K) in graphite, but at low temperatures (25 and 960 °C) [6]. Therefore, one of the ways to solve these issues is to determine or approximately evaluate the values of diffusion coefficients of the core components as a result of processing the existing experimental data according to the residual content of these components in the core-electrode system.

This work presents the results of the first attempt of mathematical modelling of the diffusion processes of the core components for an electrode with an initial diameter of 350 mm and electrodes of an increased diameter of 508 and 600 mm of two compositions (symbolic designation F_0 and F'_0).

A general view of an industrial cored electrode with an outer diameter of 350 mm used in a 12-t industrial DC furnace of the DSP PS-12 type is shown in Figure 1. In the work, the samples were used in the study taken from the lower (near-arc) region of the electrode after its 18 h operation in the furnace and a further cooling to room temperature. The samples were taken at a distance of 35 mm from the core axis and 80 and 105 mm from the core-electrode interface to determine the actual distribution of the core components in the body of this electrode (Figure 2).

PROCEDURE FOR THE DETERMINATION OF DIFFUSION COEFFICIENTS OF COMPONENTS IN THE CORE-ELECTRODE SYSTEM

The distribution of the diffusion component content in the cross-section of the cored electrode can be determined by solving the diffusion equation in a two-dimensional formulation:

$$\frac{dc}{dt} = D_C \left(\frac{d^2c}{dx^2} + \frac{d^2c}{dy^2} \right), \quad (1)$$

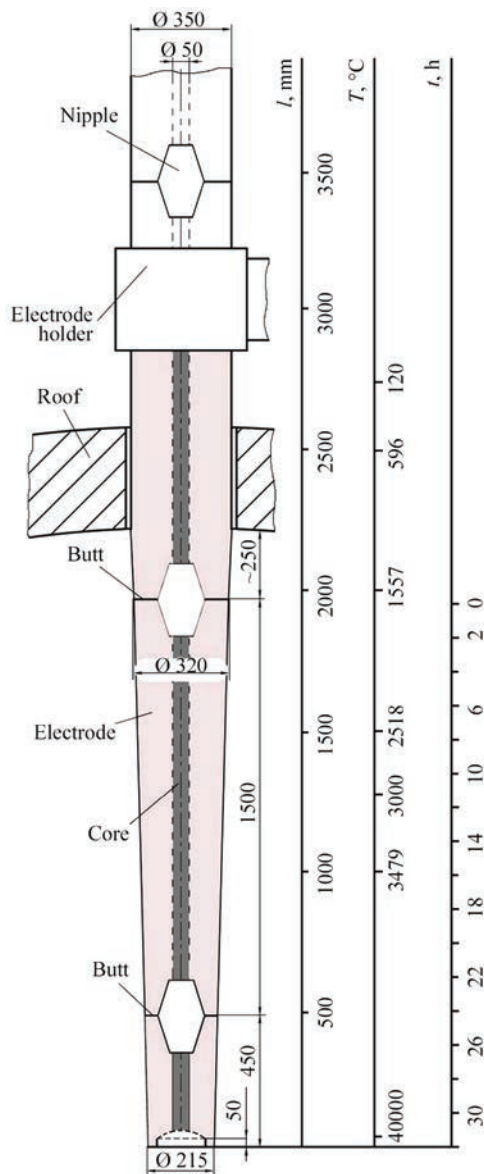


Figure 1. Temperature distribution and changes of geometric parameters in real time of the furnace operation for the cored electrode with an initial diameter of 350 mm

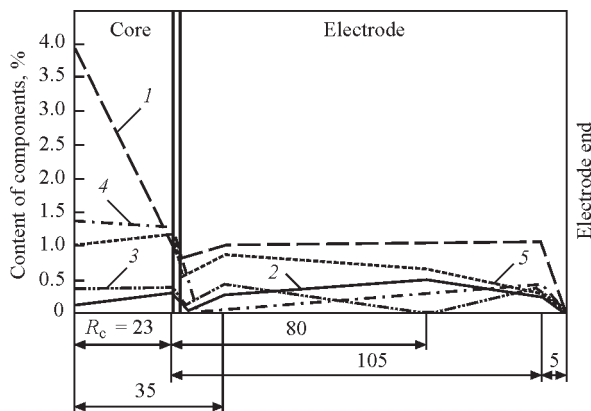


Figure 2. Distribution of the component content in the cross-section of the core and electrode with an outer diameter of 350 mm; 1 — Cu; 2 — K; 3 — Cr; 4 — Ba; 5 — Ti

Table 1. Initial content of components in the core (composition of F_0) for the calculation of diffusion coefficients, wt. %

Time, h	Cu	K	Cr	Ba	Ti
0	15.6	2.0	2.75	2.1	9.4
3	Data in Figure 2				

where c is the concentration of the diffusion components; D_c is the diffusion coefficient of the diffusion components; t is the time; x, y are the coordinates.

The initial boundary conditions:

$$c(t = 0) = c_0 \text{ — in the core at}$$

$$0 < r = \sqrt{x^2 + y^2} < D_c;$$

$$c(t = 0) = 0 \text{ — in the electrode at}$$

$$D_c < r = \sqrt{x^2 + y^2} < D_{el}. \tag{2}$$

The initial data for modelling were the actual data on the content of components in the core in the initial state (Table 1) and in the core and electrode after operation of the cored electrode with an initial diameter of 350 mm in the furnace (Figure 2). After use in the furnace, the diameter of the electrode decreased as a result of oxidation to 215 mm (Figure 1).

A two-dimensional finite element model of diffusion in the cross-section of the cored electrode was developed (Figure 3). In the core ($r < R_c = 23$ mm), the initial concentration (content) of each component was set (Table 1), in the rest of the electrode ($23 \text{ mm} < r < 105 \text{ mm}$), the initial concentration was set to zero.

Due to the lack of data on the values of diffusion coefficients of the considered components in graphite at high temperatures, it was assumed that the diffusion coefficients on the electrode temperature in the temperature range of 30–4000 °C could be determined as averaged. The time of electrode operation was set to 3 h, based on the fact that after some time from the start of the electrode operation in the furnace, as a result of diffusion, the content of the core and electrode components corresponds to that shown in Figure 2. As a result of the carried out numerical experiments, the diffusion coefficients for each component were determined under the condition of maximum coincidence with the experimental data on the distribution of the component content by the electrode radius at the end of its operation. The iterative selection of diffusion coefficients was performed at the smallest square deviations [6]:

$$\sum_{i=1}^n (f_i - f_x)^2 \rightarrow \min, \tag{3}$$

where $(f_i - f_x)^2$ is the square deviation between the actual value f_i and the corresponding estimated f_x ; n is the number of pairs of compared values.

The additional verification and correction of the experimental data on the distribution of the component content in the electrode was carried out. The total amount of the components (gain of content per volume) in the electrode after 3 h of operation should not exceed the initial amount in the core and remain approximately the same (excluding burnout losses and diffusion into the environment). The amount of the components before and after operation in the furnace can be estimated by the initial content of the components in the core and the residual total content in the core and electrode.

RESULTS OF THE DETERMINATION OF DIFFUSION COEFFICIENTS OF THE CORE COMPONENTS

Using the presented procedure, the diffusion coefficients for each component contained in the core were iteratively selected. Figure 4 shows the results of correcting the experimental data on the distribution of the content of the Ti component after operation in the furnace, provided that the amount of the component before and after the operation of the cored electrode in the furnace is maintained, as well as several calculated distributions of the content of the Ti component after the furnace operation for different iterations to determine the diffusion coefficient, indicating the standard deviation from the corrected experimental data. As a result of the iterative selection, the diffusion coefficient for the Ti component is $540 \text{ mm}^2/\text{h}$ (mean-square deviation is 0.024).

Figure 5, *a* shows the predicted calculated component distributions in the cross-section of the cored electrode with an initial diameter of 350 mm after use in the furnace, the diameter of which was reduced as a result of burning to 215 mm in accordance with the determined diffusion coefficients. It can be seen that the distributions of all components are quite uniform with a slight increase towards the centre of the electrode.

Based on the determined calculated values of the diffusion coefficients of the components and their different initial concentrations in the core, the diffusion process was modelled to predict the possible distribution of their content in the cored electrodes of an increased diameter (508 and 600 mm) after 3 h of operation in the furnace. The modelling results (Figure 5, *b*, *c*) showed that the initial component concentration in the core of the electrodes of an increased diameter, as in the electrode with a diameter of 350 mm, did not ensure the distribution of a uniform content of these

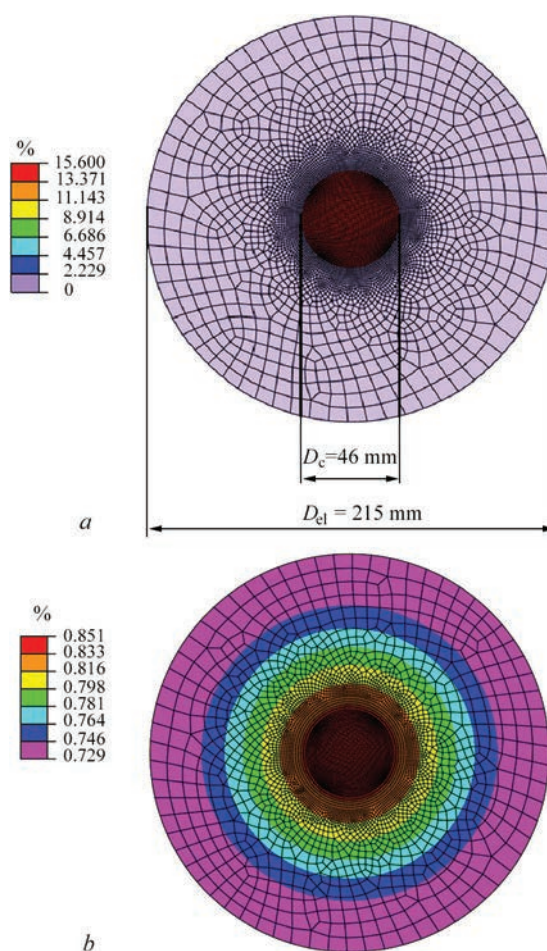


Figure 3. Two-dimensional finite element model of diffusion in the cross-section of the cored electrode: *a* — concentration of the Cu component in the initial state; *b* — after 3 h of electrode operation

components over the entire cross-section of graphite electrodes. In the cross-section of the electrode, closer to its outer surface, the content of the components

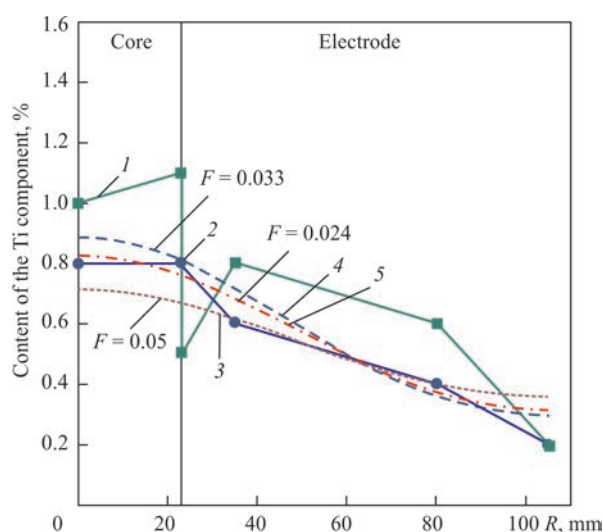


Figure 4. Experimental and calculated distributions of the content of the Ti component depending on the radial coordinate of the electrode with an initial diameter of 350 mm after 3 h of the furnace operation: 1, 2 — initial and corrected experimental data; 3 — calculated data at $D = 650 \text{ mm}^2/\text{h}$; 4, 5 — at $D = 500$ and $540 \text{ mm}^2/\text{h}$

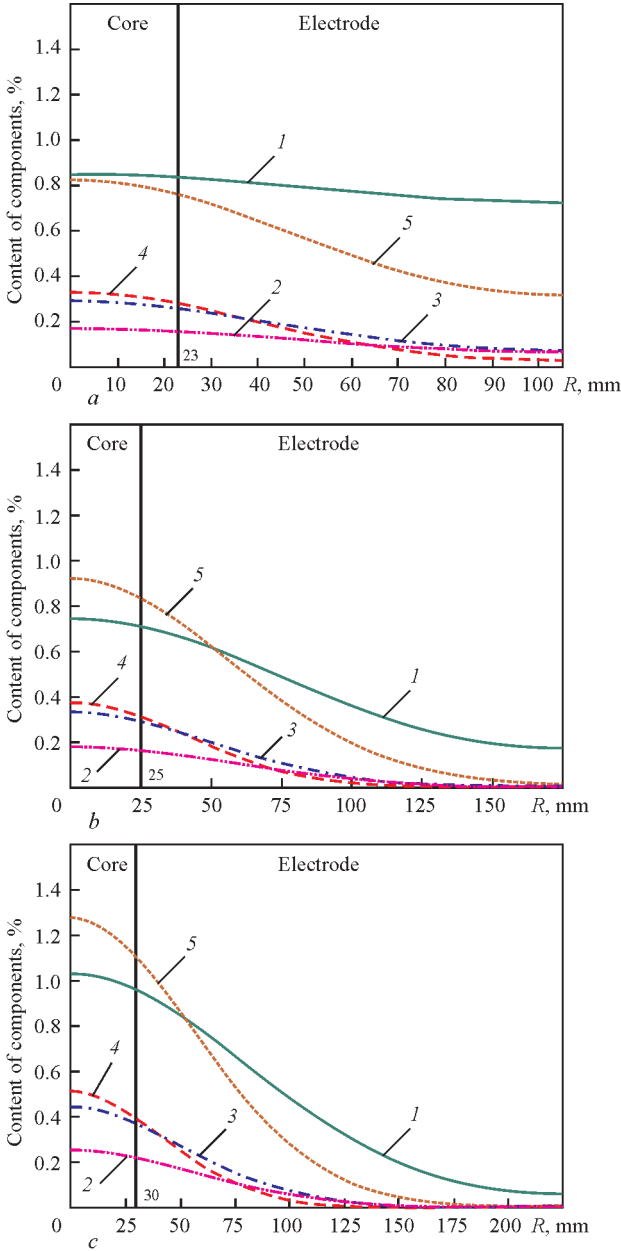


Figure 5. Estimated distributions of the content of core components depending on the radial coordinate of electrodes with initial diameters of 350 mm (a), 508 mm (b), 600 mm (c) after 3 h of the furnace operation and components and corresponding values of diffusion coefficients D , mm²/h: 1 — (Cu) 1170; 2 — (K) 620; 3 — (Cr) 460; 4 — (Ba) 290; 5 — (Ti) 540

(except for the Cu component) after 3 h of operation remains almost zero, which is a negative factor for ensuring the effective operation of the electrode.

Table 2. Limit parameters of an increased initial content of components of F'_0 in the core of electrodes with the diameters of 508 and 600 mm, wt. %

Time, h	Cu	K	Cr	Ba	Ti
0	15.6	4.0	5.5	6.6	9.4

Note. The initial content of components in the electrode is equal to zero.

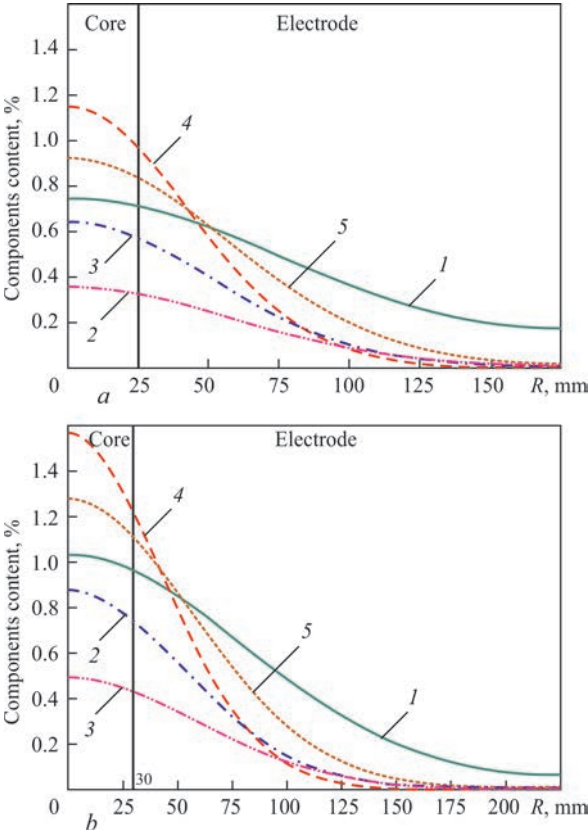


Figure 6. Distribution of the component content in the radial direction of the electrode with a diameter of 508 (a) and 600 mm (b) after 3 h of operation and components and corresponding values of diffusion coefficients D , mm²/h: 1 — (Cu) 1170; 2 — (K) 620; 3 — (Cr) 460; 4 — (Ba) 290; 5 — (Ti) 540 with an increase in the initial content of individual components in the core

Taking into account that as a result of modelling, a rather low component content was obtained in the electrodes of increased diameters (508 and 600 mm) after 3 h of operation in the furnace, it was decided to increase the initial concentration (content) of individual components in the core F'_0 for these electrode diameters (Table 2).

Based on the obtained calculated values of the diffusion coefficients of the components and increased initial concentrations of the individual components (K, Cr, Ba) in the core, the diffusion processes were modelled in the core to evaluate the possible distribution of the component content in the cored electrode with a diameter of 508 and 600 mm after 3 h of operation in the furnace (Figure 6, a, b). The modelling results showed that even a significant increase in the initial component content in the core by 2–3 times did not ensure a uniform distribution of these components in the cross-section of a graphite electrode of an increased diameter after 3 h of operation. On the periphery, closer to the outer surface of the electrode, the content of components remained very low. Only copper, due to the highest value of the diffusion co-

efficient, has a non-zero content distribution over the entire cross-section of the electrode.

CONCLUSIONS

1. For the first time, it was shown that mathematical modelling can be used to predict the distribution of components in the core-electrode system during operation in an arc furnace, taking into account the diffusion processes.

2. Due to the lack of data on the values of the considered components of the diffusion coefficients in graphite at high temperatures, it was assumed that the diffusion coefficients can be determined as averaged from the electrode temperature in the temperature range of 30–4000 °C. The time of electrode operation was set to three hours.

3. Based on the developed two-dimensional finite element model of the process of the component diffusion in the core-electrode system in the cross-section of the cored electrode and experimental data on the distribution of the content of components (Cu, K, Cr, Ba, Ti) in the initial state and after three hours of operation of the cored electrode with an initial diameter of 350 mm, in the course of numerical experiments, diffusion coefficients for each component were iteratively determined, provided that the maximum coincidence with the least square deviations with the experimental data at the end of the electrode operation in a DC arc furnace.

4. Based on the determined calculated values of the diffusion coefficients of the components and their different initial concentrations in the core, the diffusion process was modelled to predict the possible distribution of their content in the cored electrodes of an increased diameter (508 and 600 mm) after three hours of operation in the furnace. The modelling results showed that even a significant increase in the initial component content in the core by 2–3 times did not ensure a uniform distribution of the content of these components in the cross-section of graphite electrodes of an increased diameter, and at the periphery, closer to the outer surface of the electrode, the content of components after 3 h of operation is close to zero. Only copper, due to its rather high content in the core and a high diffusion coefficient, has a non-zero distribution of the content across the electrode cross-section.

5. To consider it necessary to continue the works on mathematical modelling of diffusion processes in

the core-electrode system in relation to arc steelmaking furnaces.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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