

# Certain of the thermal physics problems of reducing processes in chemical electrothermal reactors

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Presented are solutions of some problems typical for thermalphysics processes in an ore-smelting electrothermal reactor. Its reaction bulk comprises several zones of diverse phase compositions, where proceeding of physical-chemical target transformations is intensifying by turbulent energy transfer. Chemical reducing processes are proceeding on isolating the gas phase, which is bubbling the melt and actively transporting energy and reaction products. Problems of analysis of thermalphysics processes in a reaction zone and in separate elements of electrothermal reactor are considered in a two-dimensional formulation. Obtained are analytical solutions for describing thermalphysics processes in circumstances of the target product manufacturing. There is carried out structure analysis of a reaction zone and a raw material melting zone. Analytical solutions are obtained for problems of heat exchange in self-baking electrodes with regard to physical-chemical processes which take place during sintering. The electrode temperature field analysis makes it possible to guarantee reliable operative conditions and allows to form conditions needed for providing the required degree of anode paste hardening. The derived solutions may be used as references ones for numerical analysis of thermalphysics processes in a bath of ore-smelting reactors.

**Key words:** electrothermal reactor, reaction zone, thermalphysics process, mathematical model, mathematical physics equations, self-baking electrode, near-electrode processes localization.

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## Introduction

Electrothermal reactors are used for products manufacturing at high temperatures when the risk of contamination by side reagents resulting from combustion, for example, is run. The high-temperature reducing processes are accompanied by energy transmission, mechanism of which is determined by specific character of isolating the gas phase, which is bubbling the melt. Study of high-performance reducing processes is connected with inaccessibility of a reaction zone because of impermeability and presence of high temperatures. Keeping an observation on the unit's operating modes from the outside and stating the energy efficiency indexes give no information on internal structure of the reaction zone and on the coke layer and the slag melt level time history even more so, without a knowledge of which the high-quality reactor control is a considerable challenge [1–3].

That's why mathematical simulation and elaboration of adequate models are the topical problems for electrothermal ore-smelting reactors [4–10].

Approximate analytical estimations hold much significance for the computational modeling methods

setup because they allow to possess information on an order of magnitude for parameters responsible for reactor elements operation. Ignoring this approach often give wrong ideas of processes taking place in the systems. Thermalphysics processes in a reaction zone are considered in [11]. There are also obtained the approximate solutions of energy-release distribution and temperature distribution problems in a two-dimensional formulation.

Kiln gases warm the charge in an ore-smelting reactor and are refrigerating up to 300–500 °C at a furnace outlet. Temperature of gases under a furnace roof over 500 °C may cause roof destruction and, of course, is decreasing reliability of the furnace operation. Interrelationship of a reaction zone or smelt and reducing agent is fulfilled at the melting front, where a solid phase charge is converting into a liquid phase, while coke as a reducing agent is gathered or spent in the melt and forms the primary reaction space. Introduction or dosage of a reducing agent and electrode voltage serve as the key control parameters which are charged with the reactor operation.

Thermophysical processes in a bath of electrothermal reactor for reducing such products as phosphorus, calcium carbide, titanium carbide and the others proceed under the same conditions and are described by identical equations.

Thermophysical processes in a burned zone of reactor are examined in [12]. The thermal conditions of electrodes, by means of which electric power is supplied into reaction zone, are of no lesser importance. The anode paste is warmed and sintered as it is fed; it must meet the strength requirements.

### Structure of a reaction zone of an electrothermal ore-smelting reactor

To form some initial insight on the structure of a reaction zone of reducing reactor, we consider eventual realizations of the processes proceeding in a volume of reactor, based on approximate estimations. According to [13], a layer with elevated coke content, or carbon zone, should play a role of the cushion holding the charge over the melt due to its particles density lower than the charge density and much more lower than that of slag and ferroalloy. This conclusion has been derived from the mistaken interpretation of the reactor breaking after the forced stop when the coke submerged into the melt has been recognized as that being presented in the streaming down melt, which is supposedly resulted from the burden melting by gases.

Even rough estimations of the charge warming-up degree shows that the charge is getting warmed slightly and its temperature is far from the melting one. Let us show this.

Since the charge warming-up source is a convective furnace gas heat stream, which is heat-conducting over the charge skeleton, then the heat balance equation can be written in the following form:

$$G_{ch}c_{ch}(T_{ch}^c - T_{ch}^h) = G_g c_g (T_g^h - T_g^c) + \lambda_{ch} S_{ch} (T_{ch}^c - T_{ch}^h) / h_{ch}. \quad (1)$$

Whence it follows that the heat-conducting stream over the skeleton is small even without taking contact resistance into consideration.

At the listed below values of parameters:

$$\begin{aligned} T_{ch}^h &= 300 \text{ K}; T_g^h = 1600 \text{ K}; T_g^c = 600 \text{ K}; \\ G_{ch} &= 20.7 \text{ kg/s}; G_g = 4.1 \text{ kg/s}; \\ c_g &= 1.2 \text{ kJ/kg}; c_{ch} = 1.2 \text{ kJ/kg}; \\ \lambda_{ch} &= 0.8g \cdot 10^{-3} \text{ kW/(mK)}; S_{ch} = 78 \text{ m}^2; h_{ch} = 4 \text{ m}, \end{aligned}$$

we obtain  $T_{ch}^c = 603 \text{ K}$ .

Consequently, the charge is supplied to the melting zone being cold and is melted at the expense of the Joule heat emission.

Estimations of the phase's boundary line location without taking the furnace bath walls resistance into consideration may be obtained with regard to buoyancy force of the melt as follows:

$$h_c \rho_c (1 - \varepsilon_c) + h_{ch} \rho_{ch} (1 - \varepsilon_{ch}) = \Delta h \rho_{sl} (1 - \varepsilon), \quad (2)$$

where  $h_c$ ,  $h_{ch}$ ,  $\Delta h$  — height of the coke layer, charge and displaced melt respectively;  $\rho_c$ ,  $\rho_{ch}$ ,  $\rho_{sl}$  — density of the coke, charge material and slag respectively;  $\varepsilon_c$ ,  $\varepsilon_{ch}$ ,  $\varepsilon$  — fractional void volume of the coke layer, charge and particles in slag respectively. At  $\rho_{ch} = 2 \cdot 10^3 \text{ kg/m}^3$ ,  $h_{ch} = 2 \text{ m}$ ,  $\rho_c = 10^3 \text{ kg/m}^3$ ,  $h_c = 1 \text{ m}$ ,  $\rho_{sl} = 4 \cdot 10^3 \text{ kg/m}^3$  and equal fractional void volume values of the coke layer, charge and particles in slag, we obtain  $\Delta h = 1.2 \text{ m}$ . By this is meant that the coke layer is entirely submerged into the melt under the influence of the material column mains and a part of the charge material is contained in the melt, forcing it into the layer interstice. Hence, the charge comes to the melt being underheated. It is melted in a quite narrow over-coke layer, which can be considered in a volume of a furnace bath as the melting front.

Presence of a coke layer introduces some adjustments to the reaction zone operation, which is proceeding in the context of regime ambiguity at the equal values of control parameters. Plurality of steady states is typical for carbon-reducing processes at diverse structure (height) of carbon zone. The simplest model of heat emission in the reaction zone with a coke layer is based on the resistance representation as a concatenation of resistances of the coke and slag zones.

The reaction zone is governed by the heat release law for conductor with the current according to the following equations:

$$P_{el} = U_e^2 / (\xi_{el} h_{cz} + \xi_{el1} h_{sl}); \xi_{el} = \rho_{eli} / S_f, \quad (3)$$

where  $P_{el}$  — power of the Joule heat emission;  $U_e$  — electrode voltage;  $h_{cz}$  — height of a coke zone;  $h_{sl}$  — height of a slag zone;  $\xi_{el}$  — coefficient, characterizing the electrical properties (resistance) of a coke layer;  $\xi_{el1}$  — coefficient, characterizing the electrical properties (resistance) of a slag zone;  $\rho_{eli}$  — specific electrical resistance of the  $i^{\text{th}}$  zone;  $S_f$  — sectional area of a reaction zone. Correspondingly, the current in electrodes is determined by the Ohm's law as follows:

$$I_e = U_e / (\xi_{el} h_{cz} + \xi_{el1} h_{sl}). \quad (4)$$

Type of the representation model of the reaction zone resistance allows to identify the latter by measured current and voltage. However, problems of such a type are sophisticated and are noted by the great level of uncertainty [14].

An identical power educing is observed for different electrode voltage values depending on the coke zone height. As it is clearly seen in Fig. 1, regimes with different reactor capacity are possible at continuous stress. In a similar manner, the steady power lines cross the curves with different coke zone heights at various voltages. Thus, structure of the reaction zone determines the furnace capacity. Achieving the steady-state conditions at various values of internal parameters of reactor is examined in [10].

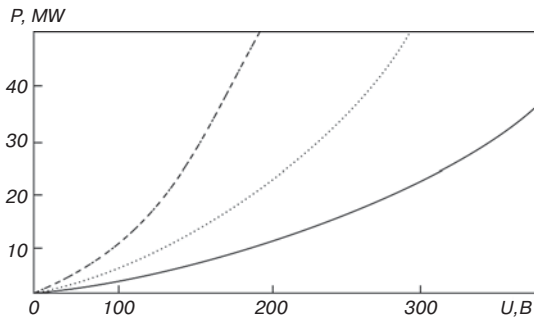


Fig. 1. The capacity dependence of electrode voltage:  
 1 –  $h_{cz1}$ ; 2 –  $h_{cz2}$ ; 3 –  $h_{cz3}$ ;  $h_{cz1} > h_{cz2} > h_{cz3}$

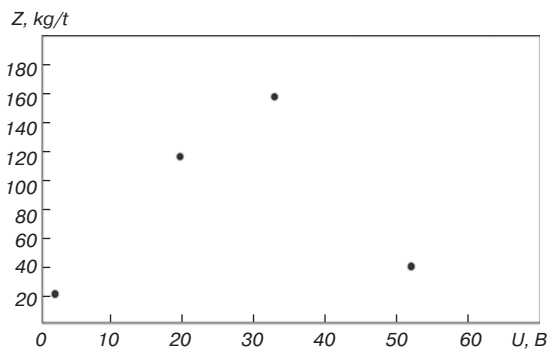


Fig. 2. The dustiness (gases rate, charge productivity) dependence of electrode voltage for a carbide furnace with capacity of 1 MW,  $\text{del} = 0.5 \text{ m}$

Mechanisms of the dustiness behaviour in the reactor charge zone are similar to that of power, which favours the assertion on ambiguity of the reactor behaviour. In Fig. 2 is represented a dependence in which a dustiness ambiguity becomes apparent. According to the hydrodynamic sliming theory, it is proportionate to reactor power [15].

The reactor control by modifying the electrode voltage necessitates availability of information on the coke zone dimensions, which is possible only approximately because of the absence of any sensors, i. e. inaccessibility of the reaction zone. There exist indirect methods of the reaction space structural identification but they are of low reliability. That's why mathematical modelling of determinate state possesses an extra appeal.

**Forming of a reaction zone during the dispersed particles of the charge melting in a melt**

Rate of incoming reagent, or charge materials in a liquid phase, is connected with melting process of the charge pieces. Therefore, the heat-mass exchange interrelationship between the liquid-phase (reactionary) and solid-phase charge zones is put into effect in a zone of phase transformations. Problem on determination of the phase transformations rates is known as a Stefan problem.

In the general setting it is quite intricate, but with some assumptions it is considered in a lot of papers, for example [16].

The distinguishing characteristics of the problem on material melting in an ore-smelting electrothermal reactor are the following aspects: the energy source presence in a melt area; the pieces melting immediately in the melt; low temperature of the pieces falling into the melt; intense melt stirring in the melting area by gases bubbling through the melt. The charge particles in passing from charging pipes to melt surface are getting warmed thoroughly by convective streams from kiln gases in a contraflow. In different circumstances of burden descent and filtration of gases, the Biot number  $Bi$  for a charge zone falls within the range between 0.04 and 0.24, that is the charge particles may be considered to sufficient accuracy as thermally thin. In that case the main braking effect is brought by heat emission and temperature inside the particle have a uniform distribution.

Melting rate of the particle heated to the melting temperature will be determined from the balance of energy incoming from the melt and spent for melting. If a particle not heated up to the melting temperature falls into the melt, the melting will be preceded by the charge piece heating which stops when the surface temperature will become equal to that of the phase transformation. Moreover, the underheated particle is getting covered by the scull skin that is a slag solid phase, thickness of which is determined by thermal capacity, dimensions and initial temperature of the particle. During smelting the small-sized charge particles, the scull skin thickness is negligible and the surface temperature reaches the melting one practically immediately.

Assuming these suppositions as a basis and taking into account the heat transmission intensity in melting area of the melt, as well as considering zone adjacent to the particle as isothermal, we will put the challenge of the charge melting description in the form of simplified Stefan problem:

$$\rho_m c_m \frac{\partial t}{\partial \tau} = \lambda \frac{1}{r^2} \left( r^2 \frac{\partial t}{\partial r} \right) \quad (0 < r < \xi); \quad (5)$$

$$\left( \frac{\partial t}{\partial r} \right)_{r=0} = 0;$$

$$\lambda \left( \frac{\partial t}{\partial r} \right)_{r=\xi} = \alpha(t_\ell - t_L) + q_s + \rho_m Q_L \left( \frac{d\xi}{d\tau} \right); \quad (6)$$

$$r = \xi, t = t_L.$$

where  $q_\alpha = \alpha(t_\ell - t_L)$  – convective heat flow towards the particle surface;  $Q_L$  – the charge material melting heat;  $q_s$  – density of a heat flow towards the front of particle melting at the expense of the Joule heat emission;  $\xi$  – coordinate of a melting front;  $r_m$  – radius of a material particle.

A variant of the integral heat balance method has been used to solve the problem. The melting rate calculation

necessitates knowledge of temperature distribution inside the particle. Since determination of temperature field from the Stefan problem solution is laborious enough [16], let us use an approximate approach for a solution search. The simplest approximation of the temperature distribution in a particle, parabolic for example, makes it possible to solve the problem on melting in an analytical way. The law of the particle center temperature changes is unknown, but at the melting start the temperature of the center is equal to the initial one, while after completing the operation it equals to the melting temperature. Assuming a linear relationship between these two states, we will obtain for the melting front coordinate:

$$\bar{\xi} = -g_1 + (g_1 + 1)\sqrt{1 - g_2\tau/(g_1 + 1)^2}, \quad (7)$$

where  $g_1 = (15/8)Q_L/(c_m\Delta t)$ ;  $g_2 = \alpha(q_\alpha + q_s)(15/8)/(r_m\rho_m c_m\Delta t)$ .  
At small  $\tau \rightarrow 0$  we have:

$$\begin{aligned} \bar{\xi} &\approx -g_1 + (g_1 + 1) \left( 1 - 1/2 \frac{g_2}{(g_1 + 1)^2} \tau \right) \approx \\ &\approx 1 - 1/2 \frac{g_2}{g_1 + 1} \tau. \end{aligned} \quad (8)$$

Melting rate is calculated according to the following expression:

$$\begin{aligned} \frac{d\bar{\xi}}{d\tau} &= -1/2 \frac{g_2}{g_1 + 1} = \\ &= 15/8(q_\alpha + q_s)/(r_m r_m (Q_L(15/8) + c_m\Delta t)). \end{aligned} \quad (9)$$

This expression differs from the simplest formula, which ignores the heating, by the fact that melting depends on thermophysical characteristics of material.

More generally it can be noted as:

$$\frac{d\bar{\xi}}{d\tau} = -1/2 \frac{g_2}{\sqrt{(g_1 + 1)^2 - g_2\tau}}. \quad (10)$$

Time of melting  $\tau_L$  of charge particle of radius  $r_m$  suits the following formula:

$$\tau_L = 2(g_1 + 1)/g_2 = \frac{\rho_m r_m (15/4 Q_L + c_m \Delta t)}{15/4 (q_\alpha + q_s)}. \quad (11)$$

Estimating of the melting rate gives the value of  $0.5 \cdot 10^{-4}$  m/s, which broadly speaking, correlates with rate values of burden descent in the furnace. Time of a piece melting is calculated by the formula (11) and lies in the range between 4 and 15 s. The obtained dependences are used for estimating rates of burden descent in the furnace at the charge-melt boundary. The pieces melting zone is

quite thin and may be considered in a furnace bath volume as a melting front.

### Heat exchange in a self-baking electrode (with regard to sintering)

Problem on heat exchange in a lower zone of the coked electrode as applied to analysis of the process of heat supply to the coking zone is based on the equation of heat transmission having regard to electrode slip with velocity not exceeding the rate of coking processes.

The coking velocity is particularly important. It determines the electrode strengthening and consequently, the slip speed. If the slip speed exceeds the coking velocity, an electrode failure may take place, which often causes to the furnace stop and faulty operation.

As any process of responding, coking is proceeding at high temperatures and therefore depends on the heat exchange conditions. The characteristic temperatures at which coking is proceeding quite intensively, lie in the range from 500 to 700 K. The characteristic response time  $\tau_R \sim [K_0 \exp(-E/RT)]^{-1}$  ( $K_0 = 110 \text{ s}^{-1}$ ,  $E = 13,600 \text{ cal/mol}$ ) is considerably smaller than the characteristic time of anode past warming-up  $\tau_h \sim l^2/a$  ( $l \cong 1.7 \text{ m}$ ,  $a = 0.8 \cdot 10^{-6} \text{ m}^2/\text{s}$ ). Thus, the heat inflow from a reaction zone determines the sintering rate in many respects.

Let us consider the coking regime in a one-dimensional approach. An equation of thermal conductivity with reference to the coking front, which is moving at the rate of  $We$ , will look like:

$$T_{xx} + (M/\delta)T_x \pm (q_R/a_e)k_0 \exp(-E_c/RT) = 0. \quad (12)$$

The boundary conditions are as follows:

$$\begin{aligned} x = 0, \quad T &= T_s, \\ x \rightarrow \infty, \quad T &\rightarrow T_\infty, \end{aligned} \quad (13)$$

where  $M = We\delta/ae$  — the Mikhelson criterion;  $\delta$  — characteristic size;  $a_e$  — temperature conductivity;  $c$  — heat capacity;  $T_s$  — characteristic carbonization temperature;  $T_\infty$  — ambient temperature.

Solution of this equation at small thermal effects  $q_R \rightarrow 0$  is the following:

$$T = T_\infty + (T_s - T_\infty) \exp[-(M/(2\delta)) \cdot x]. \quad (14)$$

To determine the linear coking speed, the well-known dependence [17] can be used:

$$W_e = K_0 \int_0^\infty \exp[-E_e/RT(W_e, x)] dx. \quad (15)$$

To calculate the integral, let us accept some simplifying assumptions. The first one concerns the exponent decomposition by method of Frank-Kamenetsky as follows:

$$\exp(-E_e/RT) \approx \exp(-E_e/RT_s) \exp[(E_e/(RT_s^2) \times (T-T_s)]. \quad (16)$$

Besides, the temperature dependence  $T(x)$  decomposition to the Taylor's series is correct at minor values of  $x$ . Taking into account the fact that kinetic function  $k_0 \exp(-E_e/RT)$  is close to zero far from the front at  $x = 0$ , applying the accepted simplifications doesn't introduce significant errors into the final expression for integral (15).

After transformations we have the follows:

$$W_e = \sqrt{\frac{a_e k_0 RT_s^2 \exp(-E_e/RT_s)}{E(T_s - T_\infty)}}. \quad (17)$$

Hence, the carbonization rate depends on anode paste properties and temperature conditions. Anode paste consists of carbon particles with diameter of  $d_p \approx 0.05$  m in a liquid binding agent in the form of coal tar pitch.

Problem on power exchange in an electrode we consider as independent of heat exchange in a burden zone or to put it more precisely, concerned with it just by means of commonality of the boundary conditions. Heat exchange between gases and the butt of the electrode is very intense, and one might assume the latter is close to that of the melt. Heat is brought to side surfaces or is abstracted to the charge zone by convection and thermal conductivity. The heat exchange problem in a simplified form might be considered as symmetrical about the axis of electrode. Heat emission during passage of current through an electrode is minor, but is characterized by concentrating in a jacket and nearby it due to scin-effect. As the electrode operates, it is fed into reaction zone with an average velocity, which is equal to operating rate. The steady-state temperature field is determined from a solution of the following task:

$$W_{eL} \rho_{eL} c_{eL} \frac{\partial t_{eL}}{\partial y} = \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_{eL} r \frac{\partial t_{eL}}{\partial r} \right) + \frac{\partial}{\partial y} \left( \lambda_{eL} \frac{\partial t_{eL}}{\partial y} \right) + q_{eL}. \quad (18)$$

The boundary conditions are as follows:

$$r = 0, \frac{\partial t_{eL}}{\partial r} = 0; \quad y = 0, t_{eL} = t_{eL0}(r); y \rightarrow \infty, t_{eL} \rightarrow t_{av}. \quad (19)$$

This problem may be written in a dimensionless form as follows:

$$\frac{1}{\bar{r}} \frac{\partial}{\partial \bar{r}} \left( \bar{r} \frac{\partial \theta}{\partial \bar{r}} \right) + \frac{\partial^2 \theta}{\partial y^2} - Pe \frac{\partial \theta}{\partial y} + \tilde{q} = 0; \quad (20)$$

$$\bar{r} = 0, \frac{\partial \theta}{\partial \bar{r}} = 0; \quad (21)$$

$$\bar{r} = 1, -\frac{\partial \theta}{\partial \bar{r}} = Bi\theta; \bar{y} = 0, \theta = \theta_0(\bar{r}); \bar{y} \rightarrow \infty, \theta \rightarrow 0,$$

where  $\theta = (t_{eL} - t_g)/t_g$ ;  $\bar{y} = y/r_{eL}$ ;  $\bar{r} = r/r_{eL}$ ;

$$\tilde{q} = \rho_{eL} J_{eL}^2 r_e^2 / \lambda_{eL} t_g; Pe = W_{eL} r_{eL} / a_{eL};$$

$t_{eL}$  — temperature of anode paste;  $t_g$  — temperature of the environment surrounding the electrode (gases, charge, melt);  $W_{eL}$  — rate of the electrode supply;  $\rho_{eL}$ ,  $c_{eL}$ ,  $\lambda_{eL}$ ,  $a_{eL}$  — density, thermal capacity, thermal conductivity, temperature conductivity of anode paste;  $\rho_{eL}$  — specific electrical resistance;  $J_{eL}$  — current density.

Method of finite integral transformations is assumed to be the most effective problem-solving procedure for problems with a source in general and for that dependent on a radial coordinate all the more. The Hankel transform

$$\bar{\theta} = \int_0^1 r J_0(\mu_k r) \theta(\bar{r}, \bar{y}) d\bar{r},$$

where  $\mu_k$  — the roots of an equation  $\mu J_0'(\mu) + Bi J_0(\mu) = 0$  ( $\mu_k > 0$ ), reduces the problem to an ordinary differential equation. The boundary conditions and formula of inversion usage allows to write the task solution in the following form:

$$\theta = 2 \sum_{k=1}^{\infty} \frac{\mu_k J_0(\mu_k \bar{r})}{(Bi^2 + \mu_k^2) J_0^2(\mu_k)} \times \left\{ \left[ \int_0^1 \bar{r} t_{eL0}(\bar{r}) J_0(\mu_k \bar{r}) d\bar{r} - \frac{\tilde{q}}{\mu_k} \right] \times \exp \left[ \left( Pe - \sqrt{Pe^2 + \mu_k^2} \right) \bar{y} \right] + \frac{\tilde{q}}{\mu_k} \right\}, \quad (22)$$

where  $\tilde{q} = \int_0^1 \tilde{q}(r) \bar{r} J_0(\mu_k \bar{r}) d\bar{r}$ .

Temperature heterogeneousness trough an electrode section in the anode paste causes thermal stresses, proportional to the temperature gradient. As a rule, maximal gradient takes place on the electrode surface, which is usually resulting in the anode paste cracking, while the electrode erosion becomes more intense on falling into the melt. The electrode experimental temperature values obtained during the course of testing are collected in the Table [13].

Results of the temperature field in an electrode calculations based on a solution of the heat exchange symmetric problem are presented in Fig. 3.

The adequacy of the solution is quite relative and coincidence with experimental figures is just showing

The results of measurements of electrode temperatures, °C

$y/r/R$	-0.99	0	0.99
600	346	364	355
550	–	420	401
500	355	522	536
400	421	651	–
200	460	763	–
0	598	1219	1207
-200	614	1100	–
-300	1350	1401	1318
-350	1246	1451	1453

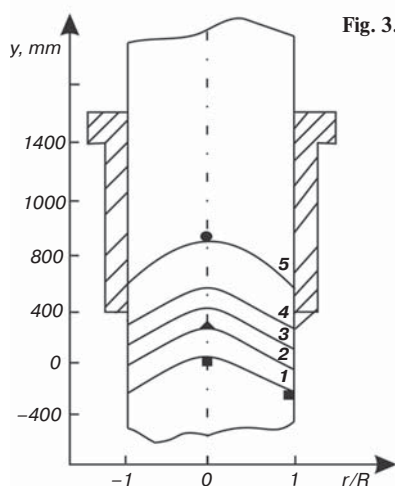


Fig. 3. The temperature field of a self-baking electrode:  
 1 – 1350 °C; 2 – 1100 °C;  
 3 – 850 °C; 4 – 600 °C;  
 5 – 350 °C

that order of values agree very closely. It is clear even in a qualitative sense, that objective fields are nonsymmetrical. However, it is obvious that trends of the fields behaviour are identical to that of objective ones and the model can be used to forecast the electrode behaviour on different thermal exposures.

### Conclusion

There is proposed an analytical approach to the thermal state analysis of some processes and elements of electrothermal reactor, which allows to draw inferences about the electrode performance data as well as about operating modes of separate zones of the reactor. The thermalphysic processes in a reaction zone of an ore-smelting electrothermal reducing reactor are examined. The resulting solutions allow to make estimations of thermalphysic processes in different zones and elements of a reactor in order to reconstruct the integrated pattern of reactor's behaviour.

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### References

1. Chumakov Yu. A., Mazmanyany V. A., Rummyantsev D. V., Tsemekhman L. Sh., Egorov P. A. Analysis of ore-thermal furnace operation at "Pechenganickel" combine under conditions of changing of charge composition. *Tsvetnye Metally*. 2014. No. 1. pp.16–21.
2. Strunskiy B. M. Ore-thermal smelting furnaces. Moscow : Metallurgiya, 1972. 368 p.
3. Kondrashev V. P., Mironov Yu. M., Kozlov A. I. et al. Investigation of operating modes of industrial electric furnaces for production of silicon carbide. *In the collection: Ore-restoring electric furnaces*. Moscow : Energoatomizdat, 1988. pp. 32–38.
4. Hariharan M., Rafi K. Mohd., Raghavan D. Modelling of calcium carbide furnace. *Bulletin of Electrochemistry*. March 1990. 6(3). pp. 298–301.
5. Eksteen J., Frank S., Reuter M. Dynamic structures in variance based data reconciliation adjustments for a chromite smelting furnace. *Minerals Engineering*. 2004. 15 (11). pp. 931–943.
6. Yang Y., Xiao Y., Reuter M. Analysis of transport phenomena in submerged arc furnace for ferrochrome production. *In: International Ferroalloy Congress, SAIMM*, 2004. pp. 15–25.
7. Scheepers E., Adema A. T., Yang Y., Reuter M. A. The development of a CFD model of a submerged arc furnace for phosphorus production. *Minerals Engineering*. 2006. 19. 1115–1125
8. Scheepers E., Yang Y., Adema A. T., Boom R., Reuter M. A. Process modeling and optimization of a submerged arc furnace for phosphorus production. *Metallurgical and Materials Transactions B*. 2010. Vol. 41, No. 5. p. 990.
9. Meshalkin V. P., Panchenko S. V., Panchenko D. S., Menshikov V. V., Kazak A. S. Computer-aided simulation of heat- and mass-transfer processes in an ore-reduction electrothermal reactor. *Teoreticheskie osnovy khimicheskoy tekhnologii*. 2015. Vol. 49, No. 5. pp. 1–7.
10. Panchenko S. V., Meshalkin V. P., Dli M. I., Borisov V. V. Computer-visual model of thermophysical processes in electrothermal reactor. *Tsvetnye Metally*. 2015. No. 4. pp. 55–60.
11. Panchenko S. V., Dli M. I., Borisov V. V., Panchenko D. S. Analysis of thermalphysic processes in near-electrode zone of electrothermal reactor. *Non-ferrous metals*. 2016. No. 2. pp. 54–61.
12. Panchenko S. V., Shirokikh T. V. Thermal hydraulics of moving dispersive layer of process units. *Teoreticheskie osnovy khimicheskoy tekhnologii*. 2016. Vol. 50, No. 2. pp. 1–8.
13. Dantsis Ya. B., Ershov V. A., Zhilov G. M. et al. Electrochemical processes of chemical technology. Ed.: V. A. Ershov. Leningrad : Khimiya, 1984. 464 p.
14. Panchenko S. V., Puchkov A. Yu., Selyavskiy Yu. V. Parametric tuning of ill-defined Kalman filter in the system of control of electrochemical reactor. *Neyrokomp'yutery: razrabotka, primeneniye*. 2016. No. 7. pp. 51–55.
15. Mikulinskiy A. S. Ore electrothermy processes. Moscow : Metallurgiya, 1966. 280 p.
16. Smurov I. Yu. Thermal processes during body smelting and ablation. *In the book: Influence of concentrated energy flows on materials*. Moscow : Nauka, 1985. pp. 108–136.
17. Shteynberg A. S. Linear pyrolysis. *In the collection: Heat and mass transfer in burning processes*. Chernogolovka, 1979. pp. 119–137.