Analysis of thermalphysic processes in near-electrode zone of electrothermal reactor

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Considered are thermalphysic processes in an ore-smelting electrothermal reactor, which is a reaction bulk with different phase composition, where transfer of energy is carried out in separate zones at temperatures above 2000 K. In the paper, a two-dimensional model of the near-electrode crucible reaction zone is presented as well as analytical solutions for describing thermalphysic processes in a reaction zone which characterize conditions of the target product manufacturing are obtained.

Experimental study of electrothermal reactor operating modes has been hampered by the absence of reliable sensors and reactionary character of the medium, that's why elaboration of the adequate mathematical models which can be realized using numerical methods is a currently central problem. However, in some cases operating figures of technological reactors may be estimated through analytical investigations owing to the use of the valid approximations. Analytical approach allows one to discover the main regularities of the influence of different factors on the process under consideration, to estimate the influence degree, to obtain a qualitative picture of an object behavior, to draw a conclusion about capability of control and extent of an effect on the control system. Calculations has been fulfilled for a technological process of phosphorus obtaining, but similarity of manufacturing processes for calcium carbide, titanium carbide, fused corundum as well as for nickel in a certain sense, gives ground to suggest that the conclusions presented in this paper are suitable for electrothermal process of a broad spectrum. There are obtained distributions of the Joule heat emission flux density, distribution of temperatures in the region of chemical and physical transformations. It is determined that target processes are localized in a near-electrode zone with the formation of crucibles unrelated. However, energy transfer processes enlarge an effective area of reactions and should be taken into account during designing and mode control. Neglecting heat efficiency may introduce large errors in analysis of the modes.

Key words: electrothermal reactor, thermalphysic process, mathematical model, mathematical physics equations, power distribution of the Joule heat sources, temperature distribution, near-electrode processes localization, reactor mode control.

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Introduction

Ore-smelting electrothermal units of carbide, phosphorus and other similar industries are the high-temperature reactors, operating conditions of which are difficult to immediate experimentally study because of high temperature and inaccessibility of a reaction zone. Therefore, the main approach to investigations of operating modes of such type of reactors is fixing the external parameters from a control panel in an inspection process and their statistical treatment [1]. Methods of measuring thermophysical parameters during survey of reactors in industrial testing are more informative [2, 3]. Results of experiments on analysis of thermal state of a burden zone of the phosphorus manufacturing furnaces are given in paper [4]. On achieving the melting zone thermocouple sensors have been falling out. Therefore, mathematical simulation of the processes in electrothermal ore-smelting furnaces (OSF) remains practically the

only way to study a behavior of so sophisticated system, described by a mathematical physics equations set [5]. The model allows one to analyze an influence of different factors on a reactor mode, which requires much less expenditures than experimental survey of the unit modes that should be carried out for quite a long time [4]. Models are convenient for working through a methodology of a furnace computer training complex for the personnel teaching [6], and also for examining problems of the furnace thermal state analysis and a computer-aided design of the furnace units.

The reduction reactor forms a high-temperature reaction zone consisting of a liquid reagent, solid reducing agent (carbon) and gas-core reaction products bubbling the liquid phase. Rate and history of reactions in a reaction zone, raw materials melting rate depend of the heat exchange processes intensity. Heat is supplied to a reaction zone from the working space of reactor owing to Joule heat generaiton. Transport processes in a reduction

zone become complicated by proceeding the heterogeneous reactions with a gas phase isolation [7], when carbon oxide bubbling intensifies agitation and have an influence upon the energy exchange, forming hydrodynamical dissipative structures [8–10]. To simulate these processes in aggregate, introducing turbulent transfer generalized coefficients is possible [8]. 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 [15, 18–20].

Mathematical model
of an ore-smelting electrothermal reactor

When modeling heat-mass exchange in an ore-smelting reactor, division of its working space into calculation zones. Model for energy exchange description comprises an electric potential distribution equations, phase motion equations, continuity and conservation of mass equations zonally and energy and mass transport componentwise.

Using the proposed in paper [6] mode of determining the effective coefficients of thermal conductivity and diffusion in gas-fluid medium, allows to bring a heat-mass transmission and hydrodynamics equations set to the thermal conductivity and diffusion equations, where hydrodynamics is taken into account by effective factors. In that case, equations of energy and mass transfer in reaction and slag zones of a ore-smelting reactor can be written down as follows:

$$\mathrm{div}(\lambda_T \mathrm{grad}\,T_f) + q_{ve} - q_{cr}\omega_{cr} = 0, \tag{1}$$

$$\mathrm{div}(D_T \mathrm{grad}\,C_f) - \omega_{cr} = 0, \tag{2}$$

Distribution of electric potential fe is defined by the equation:

$$\mathrm{div}\left(\frac{1}{\rho_e}\,\mathrm{grad}\varphi_e\right) = 0, \tag{3}$$

Heat exchange in a burden zone of reactor is determined by energy transport equations in approximation of interpenetrating components, kinematic equation for disperse material motion and filtration equation in a Darcy approximation as follows:

$$(1-\varepsilon)c_m\rho_m V_m \mathrm{grad}\,T_m - \mathrm{div}(\lambda_m\mathrm{grad}\,T_m) =$$
$$= \alpha_v(T_g - T_m), \tag{4}$$

$$\varepsilon c_g \rho_g V_g \nabla T_g - \mathrm{div}(\lambda_g \mathrm{grad}\,T_g) = \alpha_v(T_m - T_g), \tag{5}$$

$$\mathrm{div}(\mathrm{grad}\varphi_m) = 0,\ V_m = -\mathrm{grad}\varphi_m, \tag{6}$$

$$\mathrm{div}(k\mathrm{grad}\varphi_g) = \gamma\omega_{cr},\ V_g = -k\mathrm{grad}\varphi_g, \tag{7}$$

where T_f — melt temperature; C_f — concentration of reagent, for example, P_2O_5 in case of phosphorus technique

or CaO in case of obtaining calcium carbide; λ_T — effective turbulent melt thermal conductivity, cased by barbotage of light-end products of reduction reaction; q_{cr} — calorific effect of endothermic reduction reaction; D_T — effective factor of turbulent diffusion; T_m, T_g — charge and kiln gas temperature; φ_g, φ_m — potential functions in approximation of filtration gas flow and gravitational motion of disperse particles; ρ_m, ρ_g, c_m, c_g, λ_m, λ_g — density, heat capacity and thermal conductivity of burden material and gas; V_m, V_g — burden descent and gas stream velocity; $\gamma\omega_{cr}$ — source of gas mass, resulting in a phosphorus reduction reaction; $k = k_0/\mu$ — coefficient of permeability; $k_0 = 6.15\cdot10^{-4}\cdot d_m$ — coefficient of permeability for chaotically laid balls; μ — gas dynamic viscosity; αv — volume factor of heat exchange between gas and burden, which is determined by the formula $\alpha_v = \alpha f$, где $f = 6/d_{ch}$ — specific surface area of the burden particles; d_m — equivalent diameter of the burden particles; α — heat-emission coefficient for a contraflow layer. For diffusion constant and coefficient of thermal conductivity the following dependences has been used [6]:

$$D_t \approx v_t \approx k_D 4\cdot \sqrt{\upsilon_g\left(\frac{\rho_l g}{4\sigma\xi^2}\right)^{0.25}}\,\delta^{1.5},\ \lambda_t = k_\lambda \rho_l c_p D_t,$$

where $k_D = k_\lambda = 1$ — constants of proportionality for adjusting theoretical and experimental values; σ — melt surface tension; ρ_l — melt density; c_p — melt heat capacity; $\xi = 0.5$ — constant of friction; δ — typical system size; υ_g — velocity of the gas bubbling the melt.

Rate of a chemical reduction reaction ω_{cr}:

$$\omega_{cr} = (S_k/V_l)K_0\exp(-E/RT)C_1, \tag{8}$$

where S_k/V_l — specific surface area of particles of reducing agent — coke; V_l — volume of reaction zone; K_0 — preexponential factor of chemical reduction reaction constant; E — activation energy.

Capacity of heat generation in a volume unit is:

$$q_{ve} = \frac{1}{\rho_e}\,(\mathrm{grad}\varphi_e)^2 \tag{9}$$

where φ_e — a potential produced by electrodes; ρ_e — specific electrical resistance.

Boundary conditions at an upper bound of carbon zone are as follows:

$$B \in B_{melt},\ T_f = T_{melt},$$

on bath walls of the reactor (heat exchange through lining):

$$B \in B_w,\ \lambda_T\frac{\partial T_f}{\partial n} = -k_{he}(T_f - T_0),$$

where T_{melt} — burden melting temperature; T_0 — temperature of the reactor jacket cooling water; k_{he} — heat transmission coefficient. In case of an ideal insulation, temperature gradient equals to zero.

Boundary conditions for mass transfer equation at a melting front:

$$B \in B_{melt}, \ C = C_m,$$

where C_m — concentration of reagent in the burden.

Condition for the walls (impenetrability):

$$B \in B_{walls}, \ \frac{\partial C_f}{\partial n} = 0.$$

Boundary conditions for electric potential in case of polylayer zone:

• on furnace hearth:

$$B \in B_{hearth}, \ \varphi_e = 0;$$

• on electrode surface:

$$B \in B_{electr}, \ \varphi_e = \varphi_{ee};$$

• at the melt-burden border:

$$B \in B_{melt}, \ \frac{\partial \varphi_e}{\partial n} = 0;$$

• at the interface of k-th and $(k + 1)$-th conductive zones of the melt:

$$B \in B_k, \ \varphi_e = \varphi_{ek+1} \ \text{ and } \ \frac{1}{\rho_{ek}} \frac{\partial \varphi_{ek}}{\partial n} = \frac{1}{\rho_{ek+1}} \frac{\partial \varphi_{ek+1}}{\partial n}.$$

Boundary conditions for the burden temperature at an upper bound:

$$B \in B_m, \ T_m = T_{env};$$

at the melt front it equals to the melting temperature of a mineral part of the burden:

$$B \in B_{melt}, \ T_m = T_{melt}.$$

Gas temperature at the output of the reaction zone is determined as an average melt temperature in the corresponding section.

Burden descent is defined by the boundary condition at a melt front as follows:

$$B \in B_{melt}, \ \frac{\partial \varphi_m}{\partial n} = -\left(\lambda_T \frac{\partial T_f}{\partial n} - \lambda_m \frac{\partial T_m}{\partial n} \right) \Big/ (\rho_m Q_{melt}),$$

where ρ_m — burden material bulk density; T_{amb} — ambient temperature; Q_{melt} — burden melting heat.

Boundary condition on the walls (impenetrability) is the following:

$$B \in B_w, \ \frac{\partial \varphi_m}{\partial n} = 0.$$

An important peculiarity of the model is taking into consideration the interrelationship of a zonal conception as a single whole by means of including into the model of melting process, which has allowed us identify a raw material feeding to the reaction zone depending on heat-hydraulic mode in a reactor space.

Thermophysical processes in a burden zone of the technological reactor are considered in paper [4].

Henceforth, only a reaction zone is considered locally for single electrode in the form of a cylindrical bulk with an axis of symmetry, coinciding with an electrode axis. Description of physical and chemical process in the melt can be simplified in that case, basing on interaction of three localized independent reaction volumes. Problem is represented in the form of separate equations and subsystems with an assumptions of some processes being "frozen", processes localization in an under electrode space and successive examination of partial problems for different zones.

Approximate evaluation of temperature fields in a chemical reaction zone is possible with some assumptions of the constancy of reagent concentrations in a reaction volume, of the processes in the melt stationarity and of the heat emission and heat transmission processes independence. The characteristic times of chemical reaction and heat transfer differ by three orders, which may serve as a ground of such an approach.

Found out are estimations of the furnace bath state with admissions which doesn't change principal positions regarding physical essence of the problem and slightly affecting final results.

Analysis of the solution enables to establish mechanism of influence of the processes in a reaction zone on temperature changes of kiln gas in an underroof space under effects of such control parameters as coke loading, electrode voltage, granulometric burden composition and also enables to determine the furnace operating modes influence on a skull lining layer.

Calculation of electric fields and heat generation capacity in a furnace reaction zone

Let us analyze a calculated model for describing heat emission in an area restricted by dimensions of the reaction zone of a r_p radius. With an independence of a specific resistance value from temperature, the electric field potential distribution in the melt of a localized near-electrode zone will look like:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \varphi}{\partial r} \right) + \frac{\partial^2 \varphi}{\partial y^2} = 0, \tag{10}$$

with the following boundary conditions:

$$\frac{\partial \varphi}{\partial r}\bigg|_{r=r_p} = 0 \ (y \in [0, \infty]); \tag{11}$$

$$\frac{\partial \varphi}{\partial r}\bigg|_{r=0} = 0 \ (y \in [0, \infty]); \tag{12}$$

$$\frac{\partial \varphi}{\partial y}\bigg|_{y=0} = \psi(r) \begin{cases} -\rho_e j & r \in [0, r_e]; \\ 0 & r \in [r_e, r_p]; \end{cases} \tag{13}$$

$$\bar{\varphi} = \frac{1}{\pi r_e^2} \int_0^{r_e} \varphi(r, 0) 2\pi r dr = 0 \ (y = 0), \tag{14}$$

where j — density of electrode current; r_e — an electrode radius; r_p — the reaction zone radius.

Condition (11) characterizes system insulation outside the reaction zone, condition (14) reflects symmetry property of a potential. Formula (14) represents a condition of potential normalization on the electrode surface.

Method of finite integral transformations has been used for the problem solving.

Dependence of electric potential and its derivatives of the melt radius and depth are obtained in the following form:

$$\varphi(r, y) = a_{-1} + a_0 \frac{y}{r_p} + \sum_1^{\infty} a_n J_0(\mu_n r/r_p) \exp(-\mu_n y/r_p), \tag{15}$$

where

$$a_0 = -\rho_e j r_e^2/r_p,$$

$$a_n = 2\rho_e j r_e \frac{J_1(\mu_n r_e/r_p)}{[\mu_n^2 J_0^2(\mu_n)]} \ (n = 1, 2, ...),$$

$$a_{-1} = -4 r_p \rho_e j \sum_1^{\infty} J_1^2(\mu_n r_e/r_p)/[\mu_n^3 J_2^0(\mu_n)],$$

$$\frac{\partial \varphi}{\partial r} = -2\rho_e j \frac{r_e}{r_p} \sum_{n=1}^{\infty} \frac{J_1(\mu_n r_e/r_p)}{\mu_n J_0^2(\mu_n)} J_1(\mu_n r/r_p) \exp(-\mu_n y/r_p),$$

$$\frac{\partial \varphi}{\partial y} = -2\rho_e j \frac{r_e}{r_p} \left[\sum_{n=1}^{\infty} \frac{J_1(\mu_n r_e/r_p)}{J_0(\mu_n)} J_0(\mu_n r/r_p) \times \right.$$

$$\left. \times \exp(-\mu_n y/r_p) + r_e/r_p \right],$$

where μ_n — roots of the equation $J_1(\mu_n) = 0$.

Heat generation capacity in a unit of volume is calculated by the following formula:

$$q_{ve} = \frac{1}{\rho_e} \left[\left(\frac{\partial \varphi}{\partial r}\right)^2 + \left(\frac{\partial \varphi}{\partial y}\right)^2 \right]. \tag{16}$$

Temperature field in an under-electrode area (coke zone)

Approximate evaluation of temperature fields in a chemical reaction zone is possible with some assumptions of the constancy of reagent concentrations in a reaction volume, of the processes in the melt stationarity and of the heat emission and heat transmission processes independence. A distinction of characteristic times of chemical reaction and heat transfer may serve as a ground of such an approach.

Let us write an equation of heat exchange taking into account the considered assumptions:

$$\lambda_{tr} \frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right) + \lambda_{ty} \frac{\partial^2 T}{\partial y^2} - q_{cr} K_0 C_l \frac{S_k}{V_l} \exp(-E/RT) +$$

$$+ q_{vl} = 0. \tag{17}$$

Boundary conditions are as follows:

$$r = 0, \ \partial T/\partial r = 0; \ y \in [0, h_P]; \tag{18}$$

$$r = r_P, \ \partial T/\partial r = 0; \ y \in [0, h_P]; \tag{19}$$

$$y = 0, \ \lambda_{ty}(\partial T/\partial y) = 0; \ (r \in [0, r_P]); \tag{20}$$

$$y = h_P, \ -\lambda_{ty}(\partial T/\partial y) = \rho_g c_g W_g T; \ r \in [0, r_P], \tag{21}$$

where T — temperature in a reaction zone; $\lambda_{tr}, \lambda_{ty}$ — radial and vertical components of anisotropic turbulent thermal conductivity; ρ_g, c_g, W_g — gas phase density, heat capacity and rate; h_P — height of a reaction zone; S_k — reaction surface.

In that way heat exchange in anisotropic system with thermal conductivity coefficients differing in vertical and radial directions is analyzed. It is approximately accepted that heat exchange at the border of reaction zone is absent, while the heat exchange at the upper border is determined by kiln gases leaving the melt. Estimations show that the heat carry-over with gases considerably exceeds the heat flow by thermal conductivity throw electrode and burden. Heat emission localization in a under-electrode zone enables to approximate a thermal source function as a function of a form close to stepped in radial direction. Moreover, the analysis enables to represent heat generation capacity in a volume unite qve in a factorized form, in other words as a product of the functions each of which depends only of one coordinate. Since heat exchange in the considered zone is very intensive due to agitation, temperature deviations from some average value should be insignificant. That fact serves as a ground for using a reaction constant decomposition to the Taylor's series with keeping only decomposition members of the first order:

$$a\exp(-E/RT) \approx a\exp(-E/RT_.)(1 - E/RT) +$$

$$+ a(E/RT_.^2)\exp(-E/RT_.)T, \tag{22}$$

where $a = q_{cr}K_0 C_l(S_k/V_l)$; $T.$ — a carry-over temperature, as which a melting temperature T_L may be used.

Taking into account the accepted assumptions, let us write a heat transmission equation in a dimensionless form in the following way:

$$\frac{\partial^2 \theta}{\partial y^2} + \frac{1}{\bar{r}} \frac{\partial}{\partial \bar{r}} \left(\bar{r} \frac{\partial \theta}{\partial \bar{r}} \right) - \bar{b}\theta + \bar{a} + \bar{q}_v \sigma_1(\bar{r})\sigma_2(\bar{y}) = 0; \quad (23)$$

$$\bar{r} = 0, \partial\theta/\partial\bar{r} = 0; \ \bar{r} = \bar{r}_p, \partial\theta/\partial\bar{r} = 0; \quad (24)$$

$$\bar{y} = 0, \partial\theta/\partial\bar{y} = 0; \ \bar{y} = 1, \partial\theta/\partial\bar{y} = Pe_h(\theta + 1), \quad (25)$$

where $\bar{r} = r/(h_p\sqrt{\lambda_{ty}/\lambda_{tr}})$; $\bar{y} = y/h_p$; $Pe_h = \rho_r c_r W_r h_p/\lambda_{tY}$; $\bar{q}_v = q_v h_p^2/\lambda_{ty}T_L$; $\theta = (T - T_L)/T_L$; $\bar{a} = q_{cr}K_0(S_k/V_l)C_l \times$ $\times \exp(-E/RT_L)^2 h_p/(\lambda_{ty}T_L)$; $\bar{b} = \bar{a}(E/RT_L)$.

Boundary value problem has been solved by the method of finite integral transformations. Heat generation function dependence of y is expressed in the following way:

$$\sigma_2(\bar{y}) = \exp[-f(1 - \bar{y})] = \exp(-f)\exp(f\bar{y}), \quad (26)$$

where f is an empirical coefficient.

Then the problem solution has the following form:

$$\theta(\bar{r}, \bar{y}) = \frac{2h_p^2(\lambda_{ty}/\lambda_{tr})}{r_p^2} \sum_{n=1}^{\infty} \frac{J_0(\chi_n \bar{r})}{J_0^2(\chi_n)} \times$$

$$\times \left[c_1 sh(g_n\bar{y}) + c_2 ch(g_n\bar{y}) + B\exp\left(\frac{f\bar{y}}{g_n^2 - f}\right) \right], \quad (27)$$

where $g_n = \sqrt{\chi_n^2 + \bar{b}}$,

$$\bar{B} = \bar{q}_v \exp(-f)\int_0^{\bar{r}p} \bar{r}J_0(\mu_n\bar{r}/r_p)\sigma_1(\bar{r})d\bar{r};$$

$$c_1 = \frac{c_2(Pe_h shg_n - g_n chg_n) + [Be^f/(g_n^2 - f^2)](Pe_h - f)}{g_n shg_n - Pe_h \cdot chg_n};$$

$$c_2 = -Bf/(g_n(g_n^2 - f^2)), \ \chi_n = \mu_n h_p\sqrt{\lambda_{ty}/\lambda_{tr}}/\bar{r}_p,$$

μ_n — roots of the equation $J_1(\mu_n) = 0$.

Quick temperature decrease from electrode to furnace hearth allows to examine an asymptotic of a problem of heat transmission in the melt.

Let us consider a space below an electrode as a semi-infinite medium with a vertical coordinate reference point at the electrode level. In that case boundary conditions are the following:

$$\bar{y}_1 = 0, \ d\theta/d\bar{y} = Pe_h(\theta + 1); \ \bar{y}_1 = \infty, \theta \to 0. \quad (28)$$

Solution of such particular problem with the same notation as before, will have the form as follows:

$$\theta = \frac{2h_p^2(\lambda_{ty}/\lambda_{tr})}{r_p^2} \sum_{n=1}^{\infty} \frac{J_0(\mu n\bar{r}/\bar{r}_2)}{J_0^2(\mu_n)} [c_1 e^{-g_n\bar{y}_1} + Be^{-f\bar{y}_1}], (29)$$

where $c_1 = -B(Pe_h + f)/(Pe_h + g_n)$.

Here a pattern of the temperature decreasing in depth of a bath can be traced with a particular distinctness.

Calculation results give a two-dimensional picture of physical and chemical process in a reactor bulk of the phosphorous producing reactor. Taking into account the similarity of the most reduction processes, one can suppose a complete model adequacy to manufacturing processes of calcium carbide, titanium carbide, silicomanganese etc.

Adequacy of the furnace heathydraulics simulation

In connection with difficulties of researching internal structure and processes taking place in the bath of an ore-thermal phosphorus furnace concerned with high temperatures and medium aggressiveness, in most cases verification of the proposed model is possible only with data obtained form different sources, for furnaces of various types, based on the results of Inspections, sounding as well as physical simulation. Methods of physical simulation usage for processes run in different zones and units of the furnace has permitted to obtain confirmation of trustworthiness of theoretical statements, making up the grounds for its operating modes description.

Adequacy of the mathematical model is verified by quite satisfactory coinciding of calculated and experimental temperature values of gases in the burden zone, obtained as a result of industrial testing in operating furnaces by the authors and other researchers (Fig. 1), by
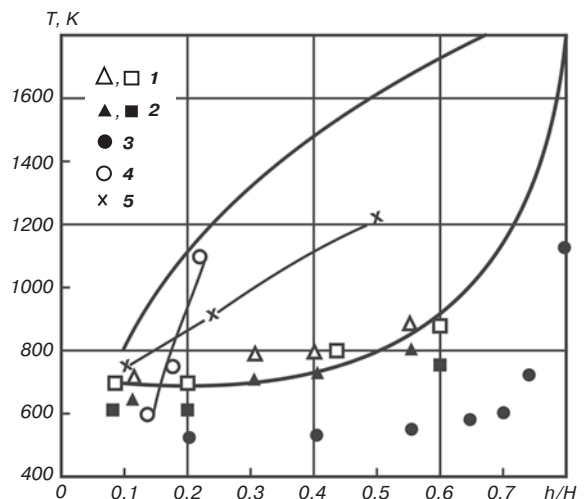

Fig. 1. Gases temperature through the furnace height:
1 — 25.30 MW, RKZ-80F; 2 — 35.45 MW, RKZ-48F; 3 — 4.5 MW, OKB-767, near-electrode areas; 4 — experiment [17], furnace periphery; 5 — furnace center; firm line — calculation [4]

experimental data for effective thermal conductivity in a reaction zone, by results of measuring fields of the burden descent rate, by results of experimental investigations of the furnace burden zone gas dynamics [8, 12, 13, 14, 16].

Results of a numerical experiment on the OSF heathydraulics completely confirm the main statements of the theoretical analysis about heat emission localization,
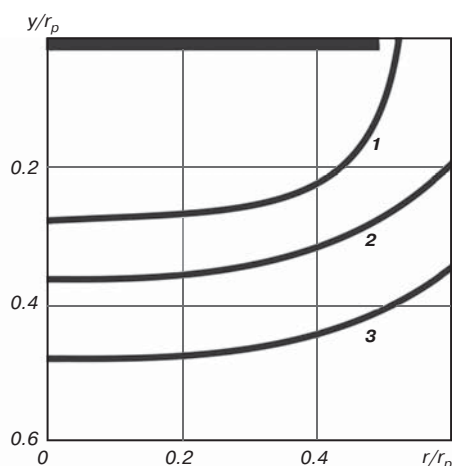

Fig. 2. Distribution of heat emission $q_v/(r_e j^2)$ in a reaction zone of the furnace when an electrode radius and a reaction zone radius are in the 0.5 relationship to each other:
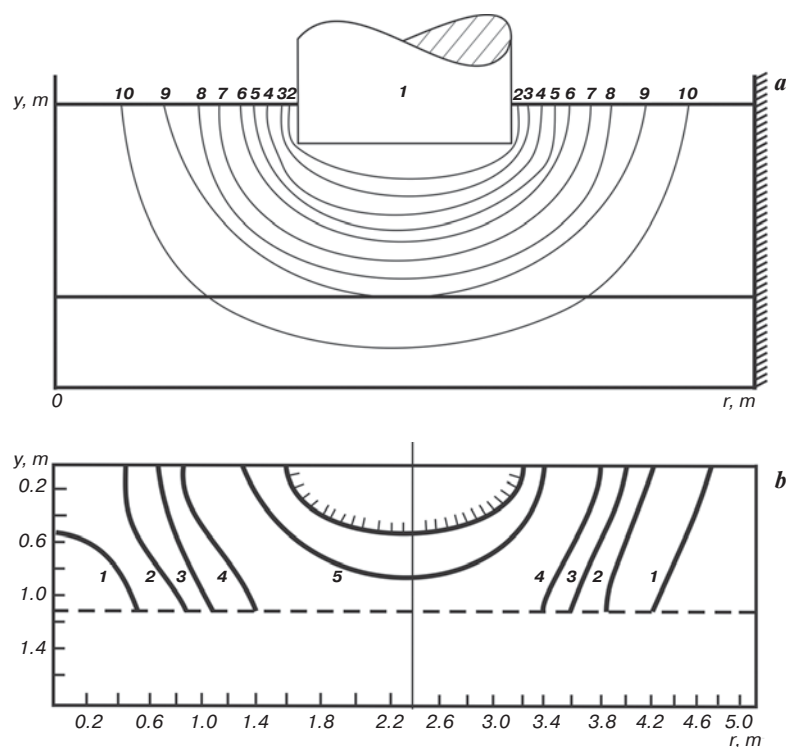*1* — 0.4; *2* — 0.2; *3* — 0.1

Fig. 3. Electric field (*a*) and energy emission density distribution (*b*) in a phosphorus furnace bath reaction zone, obtained on the basis of electrical modelling in the following coordinates: distance from an electrode to a furnace hearth — distance from a furnace axis to a wall:
a — *1* — 100%; *2* — 90%; *3* — 80%; *4* — 70%; *5* — 60%; *6* — 50%; *7* — 40%; *8* — 30%; *9* — 20%; *10* — 10%;
b — *1* — 0.1 W/cm³; *2* — 0.3 W/cm³; *3* — 0.5 W/cm³; *4* — W/cm³; *5* — 4 W/cm³

about significant heat exchange influence on operation mode of a furnace reaction zone, about irregularity of hydrodynamic and temperature fields in a furnace capacity and its effect on reliable OSF bath and arch operation [5].

Results of calculations of electric potential distribution and heat emission rate (Fig. 2) have been compared with the data of electrolytic model experiment (Fig. 3).

Electrolytic models have been used as a physical simulation method for electric potential distribution and energy-release density in the bath of a ore-thermal phosphorus furnace in papers [11, 12]. In the work [12] is considered an electrolytic model of the ОКВ-767 (ОКБ-767) phosphorus furnace 10 MW powerful. Measurement results taken from the paper [11] are presented in Fig. 3.

Calculations show an acceptable qualitative and quantitative conformity of the results obtained in the base of mathematical simulation (Fig. 2) and experimental data (Fig. 3).

Values of temperature fields in the melt allow to more acurate estimate rates of chemical reactions in a zone of chemical transformations, distribution of light-end reaction products and their temperature at the entry to a burden zone. This sort of information is especially important when estimating gases temperature in an underroof space, for heat exchange in a burden zone pattern will be mostly determined by a gas phase power budget.

The temperature fields (Fig. 4) calculations performed for a phosphorus furnace show the melt temperature decrease throughout the height.

Results of a carbide furnace industrial testing [3], transport processes in which bear a close analogy with thermophysical processes during phosphorus manufacturing [6], reveal similarity of temperature fields (Fig. 5).

In Fig. 6 the temperature distribution on a furnace throat during silicomanganese electrosmelting is shown in support of conclusions about target processes localization nearby electrodes where the most of the gas phase is educed, where take place an intense burden descent and energy exchange between burden and gases [2]. Such temperatures distribution reveals a correlation with experimental data shown in Fig. 1.
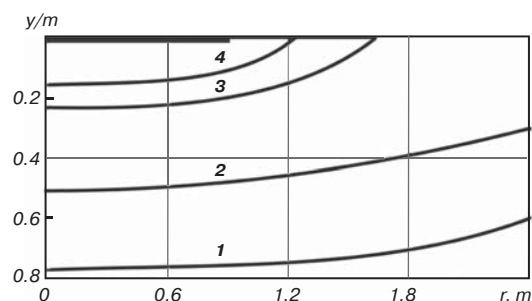

Fig. 4. Temperature field in smelt, furnace power — 72 MW:
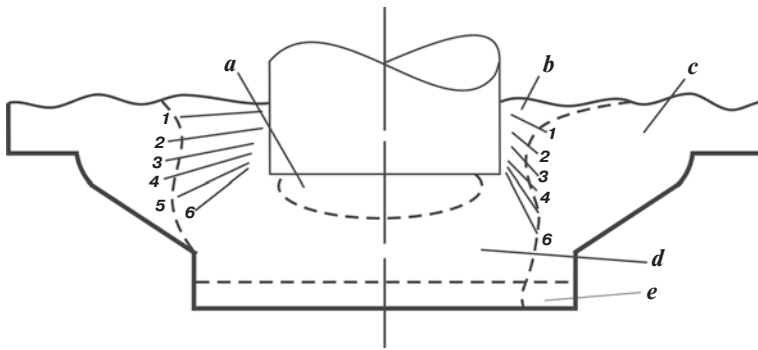*1* — 1570 °C; *2* — 1600 °C; *3* — 1700 °C; *4* — 1900 °C

Fig. 5. Sounding results for a furnace of calcium carbide production [3]. Power 60 MW, electrode voltage 130—300 V, maximum current 120 kA, burden descent rate 0.3—0.33 m/h:
a — a high-temperature zone; *b* — zone of an active burden materials descent; *c* — zone of a non-descent burden (skull); *d* — zone of a heavy slag (carbide); *e* — smelt of ferro-compounds;
1 — 750 °C; *2* — 1000 °C; *3* — 1250 °C; *4* — 1500 °C; *5* — 1750 °C; *6* — 2000 °C
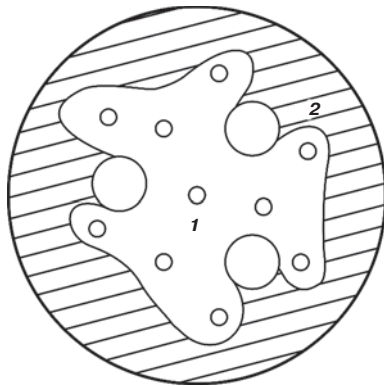

Fig. 6. Temperature on the furnace throat surface of a silicomanganese smelting furnace at the power of 9 MW:
1 — 200 °C; *2* — 1000 °C

Thermal state analysis of a reaction zone of electrothermal reduction reactor

Analysis of a furnace thermal state shows that generally heat exchange is localized close to the electrode. This suggests that electric and temperature fields of electrodes in a smelt bath of three-electrode furnaces are slightly interconnected.

The obtained bulk power distributions possess property of a reaction capacity stabilization, which appears in a volumetric capacity fractions characteristic displacement to an electrode in case of a r_p reaction crucible radius increase.

Heat emission intensity is sharply decreasing in depth of a bath. Localization of thermal sources in the near-electrode zones and heterogeneity at different deepening of electrodes are distinctly traced. Thus, the main part of reaction crucibles is separated in an under-electrode area, and a heat generating layer practically doesn't overstep the limits of a coke zone.

The temperature fields in smelt show that in an under-electrode area the smelt overheating may achieve essential values (Fig. 4). However, a high-temperature domain is also severe limited, in spite of intensive heat transmission.

Total heat emission in a three-electrode ore-thermal furnace can be obtained using an additivity property. A two-dimensional model has allowed us to investigate a spatial distribution of parameters affecting the furnace operation. Localization of the thermal pulse owing to heat emissions is achieved by intense thermal absorption in the process of endothermal reduction reactions. Temperature of waste gases determines both reliability of a unit operation and a product quality. Keeping it in the specified limits is one of important tasks for correct choice of an operational mode. As a result of calculations, reasons of the waste gas temperature rising have been determined. Irregularity of heat emission in a reaction zone stipulates unevenness of temperature distribution in a reaction zone over furnace section, which influences on a gas generation chemical reaction rate and a burden melting rate. As a consequence of that, the primary gas output with the highest temperature is observed in near-electrode zones, where also the principal burden descent takes place, despite the fact that in peripheral zones the burden practically doesn't descend. Such an irregularity results in a high temperature of the waste gases in the near-electrode areas and at the furnace periphery.

Conclusion

Proposed is a two-dimensional analytical approach to the thermal state analysis of a reaction zone of electhrothermal reduction reactor. Distribution of the Joule heat emissions energy density and temperature in a reaction zone capacity has been obtained. Calculation results display good qualitative coincidence with the data of electrical modelling and sounding reactors of various technological applications. Thus, the proposed simplified mathematical model for describing heat exchange in a furnace volume allows to reveal the primary rules of energy metabolism and to bind them with the output mode parameters. So, calculations of an average temperature of gases in an underroof space of furnaces designed for different power show that rise of the ore-thermal unit power rating leads to lessening the temperature of the gases in an underroof space. The furnace constructive parameters have an essential influence on thermal conditions by changing gas dynamics and intensity of heat-mass exchange processes.

The received results enables us to propose a strategy of the technological unit control, which guarantees high energy effectiveness and upholding of the mode restrictions necessary to keeping product quality in an admissible range. Recommendations are suitable for technologies of producing calcium carbide, phosphorus, titanium carbide, silicomanganese etc.

References

1. Chumakov Yu. A., Mazmanyan V. A., Rumyantsev D. V., Tsemekhman L. Sh., Egorov P. A. Analiz raboty rudno-termicheskikh pechey kombinata "Pechenganikel" v usloviyakh izmeneniya sostava shikhty (Analysis of the ore-thermal furnace operation at "Pechenganickel" combine under conditions of charge composition changing). *Tsvetnye Metally = Non-ferrous metals.* 2014. No. 1. pp. 16–21.

2. Strunskii B. M. *Rudnotermicheskiye plavilnye pechi* (Ore-thermal smelting furnaces). Moscow : Metallurgiya, 1972. 368 p.

3. Kondrashev V. P., Mironov Yu. M., Kozlov A. I. et al. I*ssledovaniye rezhimov raboty promyshlennykh elektropechey dlya proizvodstva karbida kaltsiya* (Research of operating modes of industrial electric furnaces for calcium carbide production). Collected articles : Ore-smelting furnaces. Moscow : Energoatomizdat, 1988. pp. 32–38.

4. Panchenko S. V., Shirokikh T. V. Teplofizicheskie protsessy v shikhtovoy zone elektrotermicheskikh rudovosstanovitelnykh reaktorov (Thermal physics processes in charge zone of electrothermal ore-reduction reactors). *Teoreticheskie osnovy khimicheskoy tekhnologii = Theoretical Foundations of Chemical Engineering.* 2014. Vol. 48, No. 1. pp. 1–6.

5. Meshalkin V. P., Panchenko S.V., Panchenko D. S., Menshikov V. V., Kazak A. S. Komputernoye modelirovaniye teplomassoobmennykh protsessov v rudovosstanovitelnom elektrotermicheskom reaktore (Computer simulation of heat-mass exchange processes in an ore-smelting electrothermal reactor). *Teoreticheskie osnovy khimicheskoy tekhnologii = Theoretical Foundations of Chemical Engineering.* 2015. Vol. 49, No. 5. pp. 1–7.

6. Panchenko S. V., Meshalkin V. P., Dli M. I., Borisov V. V. Komputerno-vizualnaya model teplofizicheskykh protsessov v elektrotermycheskom reaktore (Computer-visual model of thermalphysic processes in electrothermal reactor). *Tsvetnye Metally = Non-ferrous metals.* 2015. No. 4. pp. 55–60.

7. Panchenko S. V. Teplofizika protsessov geterogennogo reagirovaniya pri vydelenii gazofaznykh produktov (Thermal physics of heterogeneous ractions during educing gas-core products). *Trudy Mezhdunarodnoy nauchno-tekhnicheskoy konferentsii "Energetika, informatika, innovatsii — 2015"* (Proceedings of the International Scientific and Technical Conference "Power Engineering, Information Science and Innovations — 2015"). Vol. 1. Smolensk : Universum, 2015. pp. 137–141.

8. Panchenko S. V., Panchenko D. S., Glebova N. B. Protsessy perenosa v geterogennom vosstanovitelnom reaktore (Transfer processes in heterogeneous reduction reactor). Teoreticheskie osnovy khimicheskoy tekhnologii = Theoretical Foundations of Chemical Engineering. 2004. Vol. 38, No. 6. pp. 1–5.

9. Panchenko S. V., Panchenko D. S., Glebova N. B. Gidrodinamika barbotazhnogo sloya geterogennogo vosstanovitelnogo reaktora (Hydrodynamics of bubbling fluidized bed of heterogeneous reduction reactor). *Teoreticheskie osnovy khimicheskoy tekhnologii = Theoretical Foundations of Chemical Engineering.* 2005. Vol. 39, No. 1. pp. 1–4.

10. Panchenko S. V., Panchenko D. S., Glebova N. B. Formirovanie dissipativnykh struktur v reaktsionnoy zone geterogennogo vosstanovitelnogo reaktora (Formation of dissipative structures in the reaction zone of a heterogeneous reduction reactor). *Teoreticheskie osnovy khimicheskoy tekhnologii = Theoretical Foundations of Chemical Engineering.* 2005. Vol. 39, No. 2. pp. 1–6.

11. Dantsis Ya. B., Ershov V. A., Zhilov G. M. et al. *Elektrotermicheskiye protsessy khimicheskoy tekhnologii* (Electrothermal processes of chemical technology). Under the editorship of V. A. Ershov. Leningrad : Khimiya, 1984. 464 p.

12. Valkova Z. A., Dantsis Ya. B., Zhilov G. M., Antonos E. R. Issledovanie elektricheskogo polya vanny fosfornoy pechi (Research of electric field of the bath of a phosphorus furnace). *Issledovaniye i razrabotka elektrooborudovaniya i sistem avtomaticheskogo upravleniya moshchnykh rudnotermicheskikh pechey : sbornik nauchnykh trudov* (Research and development of electrical equipment and automatic control systems of high-power ore-thermal furnaces : scientific proceedings). Leningrad : LenNIIGiproKhim, 1975. Iss. 20. pp. 34–41.

13. Zhilov G. M., Valkova Z. A., Tarasov V. A., Tavrin N. Yu. Vliyanie elektrotekhnologicheskogo rezhima na paramtery pechnogo gaza fosfornoy pechi (Electrotechnological mode influence on parameters of the phosphorous furnace kiln gas). *Sovershenstvovaniye protsessov i apparatov proizvodstva karbida kaltsiya, fosfora i fosfornykh soley : sbornik nauchnykh trudov* (Improvement of processes and devices of calcium carbide, phosphorus and phosphate salts manufacturing : scientific proceedings). Leningrad : LenNIIGiproKhim, 1988. pp. 93–98.

14. Panchenko S. V., Pak M. I., Baykuchukov A. N. Raspredelenie skorostey gasovykh potokov v sloye shikhty fosfornoy pechi (Velocity distribution of gas flows in the burden layer of a phosphorus furnace). *Promyshlennaya teplotekhnika = Industrial Heat Engineering.* 1989. Vol. 11, No. 4. pp. 102–104.

15. Hariharan M., Rafi K. Mohd., Raghavan D. Modelling of calcium carbid furnace. Bulletin of Electrochemistry. 1990. No. 6 (3). pp. 298–301.

16. Panchenko S. V., Shirokikh T. V. Teplogidravlika dvizhushchegosya dispersnogo sloya tekhnologicheskykh agregatov (Heathydraulics of a moving dispersed layer of technological units). *Teoreticheskie osnovy khimicheskoy tekhnologii = Theoretical Foundations of Chemical Engineering.* 2016. Vol. 50, No. 2. pp. 1–8.

17. Ershov V. A., Reutovych L. N., Guralnik P. A. et al. O zondiorvanii vanny fosfornoy elektropechi (On probing the bath of a phosphorus electric furnace). *Tezisy dokladov Vsesouznogo nauchno-tekhnicheskogo soveshchaniya "Termiya-75"* (Abstracts of the All-Union Scientific and Technical Meeting "Thermiya-75"). Leningrad : LTI, 1975. pp. 26–29.

18. Eksteen J., Frank S., Reuter M. Dynamic structures in variance based data reconciliation adjustments for a chromite smelting furnace. Minerals Engineering. 2004. Vol. 15. pp. 931–943.

19. Yang Y., Xiao Y., Reuter M. Analysis of transport phenomena in submerged arc furnace for ferrochrome production. International Ferroalloy Congress, SAIMM, 2004. pp. 15–25.

20. 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. Vol. 19. pp. 1115–1125.

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