METHODS OF CALCULATING HEAT TRANSFER IN METALLURGICAL PLANTS AND CONTROL MODELS

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Modern deterministic approaches to constructing mathematical models and strategic and tactical control models for a production process with reference to metallurgy and labor activity are considered. Examples of using complete and simplified mathematical models to evaluate optimal conditions of production and technological processes are presented.

The need to improve the quality of a product, reduce energy and material consumption, and raise the output in metallurgy calls for development of refined methods of designing metallurgical plants, and of constructing strategic and tactical control models. In this case, by a control model is understood a mathematical model of a production process supplemented by equalities and inequalities that determine the value of optimization functions (optimality criteria) and constraints on the values of the parameters. The most important stage of designing new and reconstructing existing heat engineering plants and furnaces that provide reliable operation and the necessary production quality with the least expense is their predesign comprehensive evaluation followed by the optimization of designs and thermal and production regimes. At the designing stage these problems can be solved by using a strategic control model. The central problem of such models is associated with determining a response surface (overall dimensions) and the main energy and mass fluxes of media to realize the stated production goals. During operation of the designed plants it is necessary to determine optimal parameters of production and thermal regimes. This is achieved by the use of tactical control models. Prominent among the latter are the real time models intended for realizing computer-aided control systems of technological processes (CACS TP). During in operation of the tactical control models, optimal technological and heat engineering operating conditions are set at an already given response surface, overall dimensions, and other main elements of the design. For metallurgy this is of special importance because in the course of service the quality of the incoming raw material frequently changes, as well as the product quality, assortment, and plant capacity in connection with the diversity of orders.

It is pertinent to note that there are a number of other specific features of metallurgical plants, the combination of which imposes particular demands on the design and construction of a strategic and tactical control model for technological processes. First of all, in considering metallurgical plants, it is necessary that the physicochemical and heat transfer processes should be taken into account as interrelated. A characteristic is the motion of the treating medium, as well as of the medium to be treated (gas, liquid, and solid). This requires the processes of hydrodynamics and mechanics of continuum and dispersed media to be analyzed. Media which are used in metallurgy frequently possess temperature-dependent properties, e.g., thermally bulky bodies, for which is not only statics but also dynamics of processes are important. Usually these are high-temperature processes in which all modes of heat transfer, i.e., combined heat transfer processes, should be allowed for. These processes are complicated by the geometry and structure of the materials to be treated and of the working space. Owing to this, at the present stage, attaining the ends of strategic and tactical control as applied to heat engineering objects can be, to a better degree, realized by combining the so-called complete (higher level) and simplified (second and third level) models. It is natural that such a classification of models be sufficiently conventional since it to a certain degree "depends" on the modern level both of mathematical simulation and algorithm use and of the computer hardware (Fig. 1). As practice shows, complete models, when used for heat engineering plants, must include the heat balance and heat transfer equations in a complex statement, as well as the motion and physicochemical reaction equations. Simplified (mean level) models usually contain a two-dimensional or even a one-dimensional statement, simplified

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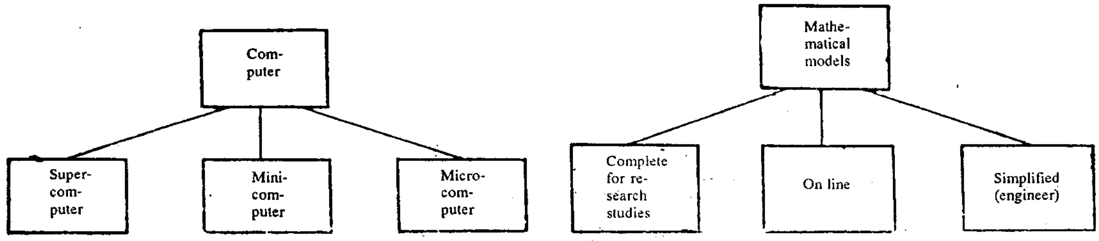

Fig. 1. Classification of computers and mathematical models.

geometry, and the differential equations often reduce to the linear statement. Finally, there are the third-level models, e.g., different polynomial models, linear dynamic with fixed parameters, etc. As follows from Fig. 1, such a classification is to a certain degree consistent with available computers: the so-called supercomputers, then mini- and macrocomputers. At the present time the concept of the complete calculation model of radiation and complicated heat transfer processes involves the possibility of allowing for the principal distinctive features of a real technological process. Moreover, both the integral and local characteristics of complicated heat transfer in a real working process are estimated (with sufficient accuracy), considering the above features. Under these conditions the basic equation of energy transfer in moving and heat transfer media,

$$\rho Di/dt = \operatorname{div}(\lambda \operatorname{grad} T) + q_v + \operatorname{div} q_{\text{rad}} \tag{1}$$

is supplemented with the continuum equations of liquid flow, motion, mass transfer, chemical reaction, boundary conditions.

As practice in research studies and designing works shows, at the present stage the demands of a sufficiently exact model of complicated heat transfer, when used for metallurgical plants, are met by the solution algorithm of equations of type (1) in the zone statement when the transition from the integrodifferential to the algebraic equations in a form accessible to numeral solution is realized. At the same time, the level of detailing the solution and the number of elements (equations) may be sufficiently large, and this provides the required accuracy and an acceptable computation time of modern computers.

At present, some writings on applied systems of multizone equations are known, including the well-established Hottel zone method, A. E. Klekel's system, and the present author's system supplemented with selective coefficients of radiation heat transfer. However, for uses of technological and, particularly, metallurgical processes where, as already mentioned, two or several thermally bulky viscous media enter into heat transfer processes, knowledge is required not only of integral but also of local characteristics. Use of these equations proves to be insufficient. If it is considered that the scheme in Fig. 2 is most typical of technological processes, where a viscous gas medium serves as the treating medium and heat carrier, and a solid or liquid thermally bulky medium is used as the medium to be treated and heat-absorbing, then in this case the zone equations of heat balance and heat transfer are supplemented with the equations of motion and heat conduction. In such a statement there arises a complex of problems on algorithm use and solution of equation systems. This has resulted in developing a new dynamic (conjugated) zone-node method (DZU-UPI-L method) (Russian abbreviation). The concept of the dynamic zone method involves solution of the conjugated problem in the zone statement of radiation convective and conductive (in a thermally bulky medium) heat transfer and that of the zone-node method, with separating out of nodes and determining local characteristics in a viscous gas medium. On the whole, the DZU-UPI-L method is used to solve the problem on conjugated heat transfer from moving viscous gas and thermally bulky media. The first realization of developing the multizone method in a conjugated statement was concerned with writing the conjugation equation for a thermally bulky medium in a regular regime [1]. The first statement of the node method was concerned with separating out the nodes in a gas medium and with determining the node generalized radiation coefficients, taking into account the nonuniformity of temperatures and optical properties of the medium [2]. At present, the model of the DZU-UPI-L method rests upon the following fundamental relations [3-9]:

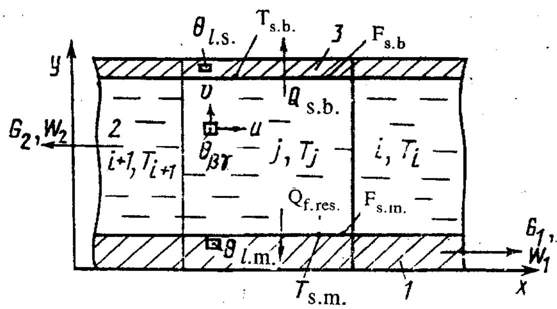

Fig. 2. Scheme of the flow model of the DZU-UPI-L method for calculating radiation and complicated heat transfer in a system of moving viscous heat transfer (1) and thermally bulky, heat-absorbing (2) media with thermally massive lining-setting (3).

1) the system of equations of heat balance and heat transfer for emitting media (in writing, in terms of the selective radiation transfer coefficients A^{Σ}_{ij} and A^{Σ}_{j}) for a zone j

$$\sum_{i=1}^{m+n-1} A_{ij}^{\Sigma} T_i^4 - A_j^{\Sigma} T_j^4 + \sum_{i=1}^{l} g_{ij} T_i - g_j T_j + Q_j = 0; \tag{2}$$

2) the equation of heat conduction in a moving medium (for material and lining-setting)

$$\rho_{l.s.}(\partial\theta_{l.s.}/\partial t) + \rho_{l.s.}c_{l.s.}w_{l.s.}\partial\theta_{l.s.}/\partial x - \nabla(\lambda_{l.s.}\nabla T_{l.s.}) - q_{s.c.} = 0 \tag{3}$$

under the conjugation condition (for a surface zone)

$$\sum_{i=1}^{m+n-1} A_{ij}^{\Sigma} T_i^4 - A_{sj}^{\Sigma} T_{sj}^4 + \frac{\lambda_{rad}}{s_{rad}}(T_{rad} - T_{sj}) = \lambda_{l.s} \left.\frac{\partial\theta_{l.s}(y,\ t)}{\partial y}\right|_{F_s}, \tag{4}$$

$$T_{sj} = \theta_{l.s.}(y,\ t)|_{F_{s.}}; \tag{5}$$

3) the energy equation for an incompressible viscous liquid (gas) flow-treating medium (two-dimensional case)

$$\rho c_p u \frac{\partial\theta}{\partial x} + \rho c_p v \frac{\partial\theta}{\partial y} = \frac{\partial}{\partial x}\left(\frac{\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial\theta}{\partial x} + \frac{\partial}{\partial y}\left(\frac{\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial\theta}{\partial y} + q^x + q^p \tag{6}$$

when the mean-zone temperature in the zone j is averaged

$$T_j = \left[\frac{1}{V_j}\sum_{\delta} \theta_{\beta\gamma}^4 V_{\beta\gamma}\right]^{1/4}, \tag{7}$$

when the density of the heat flux supplied due to radiation to a node (β, γ) in the zone j is determined

$$q_{\beta\gamma j}^{p} = \frac{1}{V_j}(Q_j^p - A_j^{\Sigma j}(T_j^4 - \theta_{\beta\gamma}^4)), \tag{8}$$

and when the resultant radiation heat flux to the zone j is estimated by the formula

$$Q_j^p = \sum_{i=1}^{m+n-1} A_{ij}^{\Sigma} T_i^4 - A_j^{\Sigma} T_j^4 \,. \tag{9}$$

Note that the source term in Eq. (3) may contain the value of the resultant radiation heat flux; then it is possible to solve the heat conduction problem for semitransparent media (slag, glass, etc.) [5].

At present, the realization of the DZU-UPI-L method has been accomplished up to applied programs. The separate procedures developed should be mentioned as an appendix to this method. These are an express-method of determining generalized radiation coefficients; 9- and 2- band models of gas radiation spectra and models for radiation of soot particles of a flame; determination of local characteristics; solution of the internal problem for a curvilinear network; determination of effective thermal conductivity of composite materials and refractory piles; estimation of scattering, complex geometry; models for burnout, ingress and soot release along flames; methods of expert estimation of mass transfer in anemometric studies of hydrodynamics, etc. [3-9].

Constructing control models for real technological metallurgical plants must not ignore the fact that relative finite temperature and chemical potentials may be considered to be assigned (fixed). In doing so, the following control conditions (autogeneration regime) [10-12] are formulated:

$$\vartheta_{Lf} = \frac{T_{Lf} - T_0}{T_1'' - T_1'} = \vartheta_{Lf}^{fix}; \ \vartheta_{ch} = \frac{C_2' - \bar{C}_2}{\rho_2(\beta'' - \beta')C_Y' L_0} = \vartheta_{ch}^{fix}. \tag{10}$$

We found that including these equalities into the models for technological processes furnishes the most important control principles, which have been specified by us as the autogeneration regime of heat transfer η_s and physicochemical η_{ch} efficiency by the ratio of the heat capacities W_1/W_2 or mass flows G_1/G_2 [10-12]

$$W_1/W_2 = \eta_s \vartheta_{Lf}; \ G_1/G_2 = \eta_{ch} \vartheta_{ch}. \tag{11}$$

As is seen, in the control mode of operation such important characteristics of processes as the ratios of heat capacities or mass flows of media prove to be closely related to the efficiency and relative potentials. In considering of the models for control of the complex of physicochemical and thermal processes, relations (10) and (11) must be taken into account together with system (2)-(9) and also (12)-(13), since for given potentials of the ratio of flow, heat capacities and mass flow rates of treating media and those to be treated cannot be prescribed arbitrarily: it is related to the values of the efficiency of the processes.

With due regard for the autogeneration regime, the simplified models of technological processes acquire a new meaning and make it possible to build the mean-level control models of physicochemical and heat transfer processes, to make an express-analysis of these processes and, in a number of cases, also to obtain analytical solutions for extreme problems. As noted, the results of such an analysis can be refined by using the complete models of type (2)-(9). As applied to metallurgical processes, the linear heat and mass transfer equations, e.g., for complex physicochemical and heat transfer counterflow, may fit into a group of the simplified second-degree equations:

$$G_2 dC_2 = -\rho_2 k_{ch} (C_2 - \bar{C}_2) dF_x, \tag{12}$$

$$W_2 dT_2 = -k_\Sigma (T_2 - T_1) dF_x. \tag{13}$$

A characteristic of our consideration is the complex correlation of physicochemical and heat transfer processes (which were, as a rule, considered separately) using the control conditions – relations of given mass and heat transfer potentials (autogeneration).

Obeying the relations for autogeneration (1) reveals a number of new effects [10-17] even in analyzing these simplified equations. These effects have a dominant role in determining the most significant features of technological process control.

Early models (12), (13) were analyzed at some assigned ratios of mass or heat carrier flows. In the autogeneration regime mentioned, these ratios are related by Eq. (11). This situation brings into existence the following physicochemical (mass transfer) and heat transfer effects.

1. The behavior of the efficiency–intensity (e–i characteristics) curves, which determine the main mass and energy flows of treating media in heat engineering plants in terms of physicochemical and heat transfer efficiency, changes substantially. For linear heat and mass transfer (counterflow) problems, the following relations are obtained:

$$\eta_{ch} = 1 - e^{(-Z_{ch} \eta_{ch} \vartheta_{ch})}, \tag{14}$$

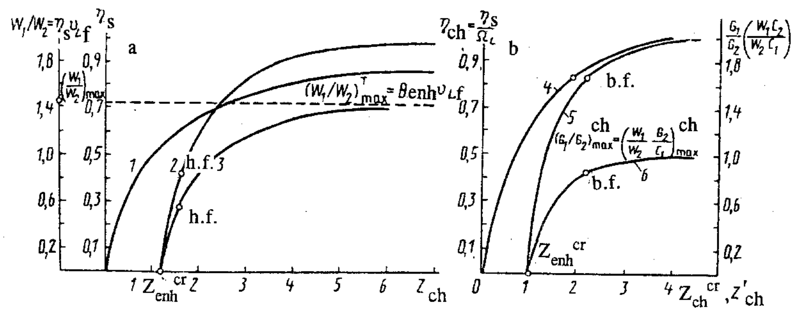

Fig. 3. e–i characteristics for heat and mass transfer processes. Thermal efficiency η_s and ratio W_1/W_2 vs heat transfer enhancement density Z_{ent} (a), and the physicochemical efficiency η_{ch} and the ratio G_1/G_2 vs physicochemical enhancement densities Z'_{ch} and Z_{ch} (b); 1) η_s at $W_1/W_2 = 1 =$ const (no autogeneration); 2) η_s at $W_1/W_2 =$ varia (at autogeneration, $\theta_{enh} = 1$, $\vartheta_{Lf} = 1.429$); 3) W_1/W_2; 4) $\eta_{ch} = f(Z_{ch})$ at $G_1/G_2 =$ const (no autogeneration); 5) $\eta_{ch} = f(Z_{ch})$ at $G_1/G_2 =$ varia (at autogeneration, $\vartheta_{ch} = 1$); 6) $G_1/G_2 = f(Z_{ch})$; Z^{cr}_{enh} corresponds to the lower-level crises; $(W_1/W_2)_{max}$ and $(G_1/G_2)^{ch}_{max}$ mean the upper level crises; h.f.are parameters of a sectionally heating furnace and b.f. are parameters of a blast furnace top.

$$\eta_s = \theta_{enh} \frac{1 - e^{(-Z_{enh}(\eta_s \vartheta_{Lf} - 1))}}{1 - \frac{1}{\eta_s \vartheta_{Lf}} e^{(-Z_{enh}(\eta_s \vartheta_{Lf} - 1))}}, \tag{15}$$

$$Z_{ch} = \frac{K_{ch}\ \rho}{G_1}; \ Z_{enh} = K_\Sigma F/W_1. \tag{16}$$

The points of a physicochemical and heat transfer crisis of the lower level are seen in the e–i curves, the condition for the relationship between the parameters of these crises existing. The curves of the e–i characteristics in the autogeneration regime go much more steeply than at fixed values of the ratios of mass or heat carrier flows (Fig. 3), i.e., the degree of the "risk" of penetrating into the crisis zone for heat transfer processes is essentially great. The upper-level crisis in the e–i characteristics curve under autogeneration manifests itself evidently in the presence of the maximum values of the mass and heat carrier flow ratios dependent on the corresponding relative potentials.

2. A close relationship between physicochemical and heat transfer efficiencies has been revealed by

$$\eta_s/\eta_{ch} = \Omega_L = \frac{\vartheta_{ch}}{\vartheta_{Lf}} \frac{c_1}{c_2}. \tag{17}$$

3. Use of the concepts about different modes of generations (thermal, chemical–chemical, chemical–thermal) in terms of the efficiency category enables one to construct a generalized topology of complex physicochemical and thermal processes and to derive a formula for the generalized chemical–thermal efficiency of the process, which determines the total energy expenditures for chemical changes and thermal processes η_Σ [12]

$$\eta_\Sigma = \frac{1 + \Delta q_s/\Delta q_{ch}}{\beta_{ch}/\eta_{t.ch} + \beta_t/\eta_t + b_{du}/\Delta q_{ch}}. \tag{18}$$

In this case, the relationship between the final physicochemical and heat transfer efficiencies is followed through the physicochemical and heat transfer efficiencies involved in these formulas.

Relations (11)-(13) make it possible to analyze the control models dramatically and to reveal the most effective modes and relationships between different generations in order to obtain the most generalized efficiency.

The examples of the use of the control models given below point to the possibility of establishing optimal situations in different technological processes and regimes. In doing so, it has been possible to directly apply complete models for the tactical control ones.

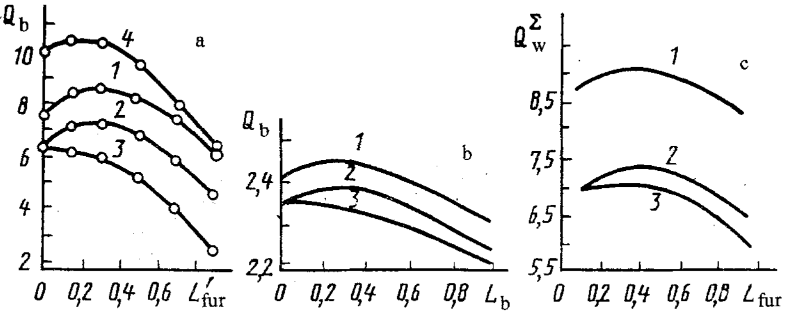

Fig. 4. Vibration of the resultant heat flux to the bath Q_b (a, b) and furnace-enclosure walls Q^{Σ}_w along the working space (L'_{fur}, L_b, L_{fur}, relative length) [a) open-hearth furnace; b) glassmaking furnace; c) flame tube furnace of the gas industry]: 1, 4) oil, luminous flame; 2) natural gas, luminous flame; 3) natural gas, nonluminuous flame; 1-3) multi-zone and 4) simplified models. Q_b, Q^{Σ}_w, MW.

On this point, the example of a luminous flame length optimal with respect to heat transfer (tactical control model) is distinctive. The result for the first time obtained numerically on the zone model of an open-hearth furnace [3] is supported thereafter for steel melting furnaces [18], and for furnaces of the oil and gas industry [5].

As compared to the one-dimensional model, use of the zone model made it possible to adjust the position of an optimum and its value (Fig. 4) [3, 5]. Note that the use of the complex optimality criterion

$$F_{opt} = AQ_{res} + BK_{non} \tag{19}$$

allows one also to judge about the optimality of a nonluminous flame (about 1/4 of the working space length). For a furnace arch flame the optimum with respect to heat transfer from the nonluminous flame, although it is very smoothed, also makes itself evident [5].

The DZU-VPI-L method has wide use in developing the tactical control model: for dynamic optimization of operating conditions of moving-metal heating surfaces. The closed control model of unsteady heating of metal incorporates the DZU-UPI-L model, dynamic models for the transducers of temperatures and local automation of furnace sections, as well as a detachable unit for process optimization. For express-calculations of optimal thermal operating conditions in real time with varying output, a method has been developed which is based on the interrelation of the simplified (mean level) and detailed models. The control model has allowed one to make some recommendations on improving the thermal operation of annular furnaces of the Pervoural Novotrubnyi Plant and Nizhne-Tagil Metallurgical Plant. In particular, these recommendations refer to sizes of the transition section-buffer memory at variable furnace output [19].

For revealing the strategic goals in designing technological processes of great importance is the integrated use of mean-level control and complete models. In doing so, the e−i characteristics are the most important basis for solving different optimal problems. So, the use of the linear models and the formulas for the thermal efficiency η_t in the form

$$\eta_t = \eta_s \frac{1 - \eta_u \ (1 - \eta_r)}{1 - \eta_r (1 - \eta_s)} - \eta_u' \tag{20}$$

allows the strategical control model to be adopted for analysis of simultaneous heat transfer enhancement in the working furnace space, i.e., enhancement due to simultaneous increases of the efficiency of the working space and heat exchanger (Fig. 5) [15]. As seen, in this case the optimal values of the heat transfer efficiencies and regeneration degrees are revealed, which become more clear when the autogeneration phenomena are taken into account and the enhancement parameters are considered. For example, to reach η_t equal to about 0.8 (according to the conditions of complete heat engineering reconstruction [1]) the quantities amounting to 0.65 and 0.5 [15] prove to be applicable for η_s and η_r.

Use of the control models allows, for example, the most important problem on the strategy in designing energy expenditures and capital expenses for the given technology to be solved. In this situation, the optimality criterion is assigned in the form [20]

$$J_{\eta F} = Ab_t + BF. \tag{21}$$

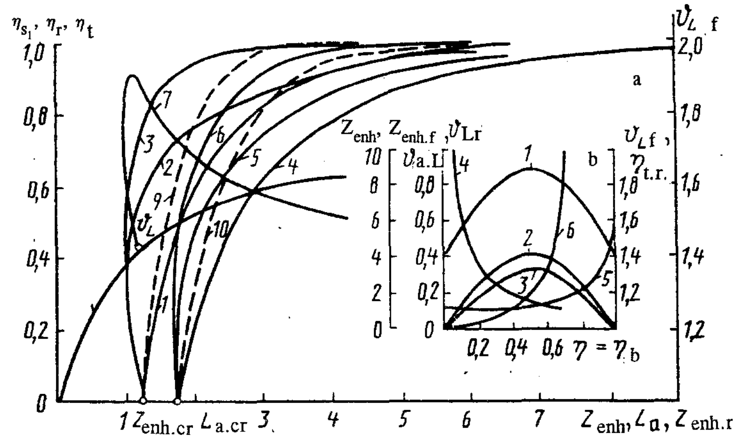

Fig. 5. e–i characteristics under simultaneous enhancement of thermal operation of the furnace. Heat transfer efficiency η_s with respect to the temperature potential ϑ_{Lf} vs enhancement density center of the working space Z_{enh} and generalized enhancement criterion L_a, as well as vs enhancement density center of the heat exchanger $Z_{enh.r.}$ (a) and relative temperature potential of the working space ϑ_{Lg}, relative temperature potential, of the regenerative device ϑ_{Lf}, relative air heating ϑ_{aL}, relation $\eta_{t.r.}$, enhancement density center for the working space Z_{ent} and the regenerative device $Z_{ent.r.}$ vs. thermal efficiency η_s (regeneration degree η_r) (b) under simultaneous first-kind enhancement in the counterflow: (a) 1-3, 7-9) quantities in the function Z_{ent}, $Z_{ent.r.}$; 4-6, 10) quantities in the function L_a; 1, 4) η_s, no regeneration; 2, 3, 5, 6, 8-10) quantities under simultaneous enhancement; 2, 5) η_s; 3, 6) η_t; 7) ϑ_{Lf}; 8) $\eta_r = f(Z_{enh.r.})$; 9, 10) $\vartheta_{Lf} = \text{const} = 1.429$; (b) 1) ϑ_{Lf}; 2) $\vartheta_{a.L}$; 3) $\vartheta_{t.r.}$; 4) ϑL.r.; 5) Z_{ent}; 6) $Z_{enh.r.}$; $L_a = \vartheta_{Lf} Z_{enh.}$; $\eta_{t.r.} = (\eta_t + \eta'_u)/\eta_s$; $\vartheta_{a.L} = T_a\text{-}273/T_L\text{-}273$; $T_L = T'_2$, no air heating.

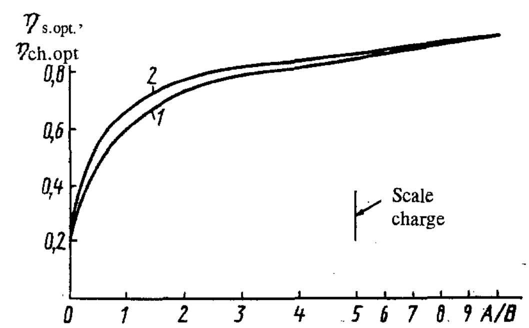

Fig. 6. Optimal heat transfer efficiency $\eta_{s.opt.}$ or physicochemical $\eta_{ch.opt.}$ vs. weight coefficient ratio A/B for fuel consumption and capital expenses: 1) no autogeneration; 2) under autogeneration. $W_1 = \infty$, $C_2 = \text{const}$.

Based on linear models using the autogeneration phenomena, the experimental values of functional (21) are found for different flow patterns. Here, the value of the optimal physicochemical or heat transfer efficiency depends on the ratio A/B (Fig. 6).

The examples presented illustrate the efficient use of the control models for solving the urgent problems on strategy and tactics in designing and servicing production plants. The theory of the complex interrelated heat and mass transfer efficiencies and the e–i characteristics under control (autogeneration) being a basis for strategical and tactical control of technological processes requires further development and support by calculations, including those obtained by modern (complete) mathematical models.

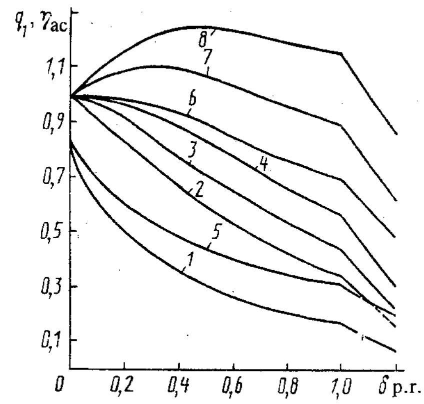

Fig. 7. Model for the endooptimality of the profit: labor activity efficiency η_{ac} (1-4) and relative useful products q_1 (in cost shares) (5-8) vs the profit rate $\delta_{p.r.}$. Values of the labor activity intensity K: 1) 5-2; 2) 6-5; 3) 7-7; 4) 8-10. Values of the complex extensive labor activity factor $\mu = \mu_{max}$ correspond to the extremal conditions by the real labor share in the cost ρ_{max}; total potential effectiveness coefficient $\varkappa_\Sigma = 1$.

Note that by using linear control models and the e−i characteristics it is possible to analyze the most important phenomena of labor activity at enterprises and on larger scales. In the area of simulating labor activity, the limited probability approaches are mainly predominant, and economic systems are more frequently analyzed on the basis of the so-called production functions relying on statistical data. Use of potential and transfer theory for analyzing labor activity makes it possible to construct a deterministic labor activity model in the form [21]

$$dQ = g_{out}\,\beta dv = K(\varkappa_\Sigma v_{work} - v_1)\,dF_e. \tag{22}$$

In formula (22) the magnitude of the potential of the labor activity is a share of the real labor in a pure product (national income), and the remaining motive factors of labor activity are taken into account in terms of the complex coefficient of the labor potential effectiveness $\varkappa_\Sigma$. Analysis of this motivation relationship and inclusion of the concept of the labor activity η_{ac} into consideration have allowed complex control models of the labor activity to be constructed, with regard to a balanced economy: production level of useful products (expenditures), general and consumer inflation, extended reproduction, and the increase in material well-being [22]. In some cases, the analysis has found the extremal situation when these or those parameters and indices of labor activity have been changed. So, by definition and according to model (22) the magnitude of relative useful products is

$$q_1 = \frac{Q_1}{C} = \eta_{ac}(1 + \delta_{p.r.}) = \varkappa_\Sigma (1 - e^{(-K\mu)})(1 + \delta_{p.r.}). \tag{23}$$

In formula (23) the quantity μ is a complex extensive labor activity factor which may be expressed in terms of the real labor share in the cost ρ_c and in terms of the profit rate $\delta_{p.r.}$:

$$\mu = \frac{\rho_c(\rho_c - 1)}{(1 + \delta_{p.r.})(\rho_c + \delta_{p.r.})} \tag{24}$$

The analysis shows that in the case of $\delta_{p.r.}$ = const at a certain value of $\rho_c = \rho_{max}$, a maximum of the quantity $\mu = \mu_{max}$ is attained and, accordingly, at an assigned value of K, a maximum of η_{ac}. As follows from formula (24) the value of ρ_{max} is

$$\rho_{max} = \sqrt{\delta^2_{p.r.} + \delta_{p.r.}} - \delta_{p.r.} \tag{25}$$

In turn, at $\rho_c = \rho_{max}$ (see formula (22)) the maximum production of relative useful products q_l takes place at a certain value of the profit rate $\delta_{p.r.}$ and a sufficiently high level of labor activity (Fig. 7). Therein manifests the law of the profit endooptimality, whose account is of very great practical importance when the contribution of the motivation factors of labor activity to the production effectiveness increase is specified.

Thus, use of the fundamental tenets of transfer theory enables one to work out unique methodological approaches when deterministic control models are being constructed for technological processes and for labor activity, naturally, with due regard to the whole complexity and peculiarity of the latter.

CONCLUSIONS

1. The deterministic approach to constructing the strategic and tactical control model of technological processes in metallurgy can be realized when complete and simplified models are used with consideration for simultaneous heat transfer and physicochemical processes.

2. As applied to the heat transfer processes in high-temperature moving media and in lining-setting, at the present stage the complete model is realized in the form of the dynamic zone-node calculation method (DZU-UPI-L method), which combines use of the zone method and solution of heat conduction problems for a medium to be treated and for a treating medium (combination of large and small networks).

3. As applied to control problems when relative temperature and physicochemical potentials are prescribed the heat transfer and physicochemical efficiencies are related by the ratios of the heat capacities and mass flows of media (autogeneration).

4. Under autogeneration conditions, the e−i characteristics of the heat transfer coefficients are distinguished by a large steepness, the phenomena of the lower and upper crises take place. The interrelation between the efficiency of the heat transfer and physicochemical processes shows itself as a relative potential of the physicochemical and thermal effect.

5. On the grounds of the transfer equations the deterministic approach is developed to construct the motivation labor activity and control models.

6. Use of the complete and simplified control models permits the specific optimality conditions for technological and designing situations to be found: flame length optimum; heat transfer efficiency-to-regeneration degree ratio for simultaneous enhancement; fuel consumption-to-capital expense ratio; profit rate optimal by the effectiveness (profit endooptimality law).

NOTATION

ρ, medium density; t, time; i, medium enthalpy; λ, thermal conductivity; T, θ, temperature; q_v, intensity of internal heat sources; q_{rad}, vector of heat transferred by radiation; m and n, number of volume and surface zones; A^{Σ}, radiation transfer coefficient; g, convective transfer coefficient; Q_j, heat sources; c, heat capacity per unit volume; $w_{l.s.}$, velocity along the x-axis; x, y, z, coordinates; $q_{s.t.}$, source term; s, layer thickness; u, v, gas velocity components; c_p, gas heat capacity at constant pressure; μ_t, turbulent viscosity; Pr_t, turbulent Prandtl number; q^{ch}, heat release power due to chemical reactions; q^r, heat by radiation; δ, number of nodes; V, volume of a zone or node; $A^{\Sigma j}{}_j$, radiation to answer coefficient proportional to the intrinsic radiation flow leaving the zone h; C, concentration of a reagent to be treated; C_2, equilibrium concentration; C'_j, initial concentration of a reagent in a treating medium; ϑ, relative initial potential; L_0, theoretical reagent flow rate necessary for complete reaction; η, efficiency (effectiveness); η_s, heat transfer efficiency; η_{ch}, physicochemical efficiency; W, flow heat capacity; G, mass flow; F_x, surface; k_{ch} and k_{Σ}, total heat and mass transfer coefficients; Z_{ch} and Z_{enh}, enhancement density centers of heat and mass transfer processes; Q_L, relative potential of the physicochemical and thermal interaction; η_{Σ}, generalized chemical−thermal efficiency; $\eta_{t.ch.}$ and η_t, final physicochemical and thermal efficiencies; Δq_{ch} and Δq_u, useful energy expenditures for chemical and thermal processes; β_{ch} and β_t, effective resistances determined by the extent of using chemical−thermal regeneration, thermal efficiency of an extra modulus and other factors; $b_{d.r.}$, energy expenditures for direct use of a reagent; F_{opt}, complex optimality criterion; Q_{res}, resultant heat flux; K_{non}, degree of heating nonuniformity; A, B, weight coefficients; η'_{loss} and η''_{loss}, coefficients of heat losses by the working space and under chemical and mechanical incomplete combustion; η_r, regeneration degree; $J_{\eta F}$, optimality criterion with respect to heat flow rate and capital expenses; b_f, specific fuel flow rate; Q, output (commercial products); v_o and v_1, effective labor potential and current potential per labor product; K, labor activity intensity; F_e, extensive factor of the labor activity (last labor); g_{out}, output; $\beta = N$, labor activity capacity; N, pure products (national income); q_1, relative magnitude of useful products; Q, useful products; C, cost; η_{ac}, labor activity effectiveness; $\varkappa_\Sigma$, complex coefficient of the labor potential effectiveness; μ, complex extensive factor of the labor activity; $\Delta_{p.r.}$, profit rate. Indices: i, j, s, m, l.s., zones transferring and absorbing the heat, surface, material, and lining-setting; b, liquid or solid body (lining-setting material); l, laminar boundary layer at the zone-surface boundary; L_f, 1, 2, 0, ′, ″, inlet temperature parameters of the heating medium, the medium to be treated, the treating medium, and the surrounding medium at the inlet and outlet; ch, chemical potential; fix, assigned potential; $\beta\gamma$, node.

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