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A MODEL PREDICTIVE APPROACH TO BLAST FURNACE OPERATIONAL MANAGEMENT AUTOMATION

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Blast furnace operational management automation using modelling and real-time predictive solutions for the object control are considered. Main features of the proposed control are: using of an operational data mining software to identify effective clusters of the furnace regime parameters values; real-time software for identification of the furnace cohesion zone parameters for the operational management correction; dynamics forecasting of the furnace thermal state indicators when charge load and blast parameters change.

Usage of the software permits to achieve effective values of the furnace regime parameters with high productivity and reduced coke consumption. It is effective in conditions of the significant charge parameters changes, due to using of source materials from different suppliers. Therewith, forecasting of parameters dynamics allows supervisor to stabilize the blast furnace process in the effective regime.

The system is based a joint development of the South Ural State University (National Research University), "Polytech-Automatica" Research & Production Ltd. (Chelyabinsk) and "AKOMM" Ltd. (Moscow).

Keywords: blast furnace process, model predictive control.

Introduction

A promising work direction to improving the efficiency of blast-furnace processes control is application of methods, based on modeling and predictive solutions.

In general, the use of blast furnace models has a great history and a large number of sources on this topic is available.

It is necessary here to note the works of national authors I. Tovarovskiy, A. Gotliba, G. Efimenko, A. Gimmelfarb, A. Pokhvisnev, O. Onorine, N. Spirin, A. Ramma, A. Dmitriev [1–26]. The works of V. Parshakov [12–15], devoted to study of influence of the cohesion zone parameters on the blast furnace process efficiency, deserve special attention. It is necessary to note among foreign authors the works of J. Kule, M. Sasaki, K. Ono, A. Suzuki, J.M. Burgess, D.R. Jenkins, K.L. Hockings, S.A. Kumar, N. Suresh, C.P. Jeffreson, M. Gobetto [27–41].

However, as far as the blast furnace process is quite sophisticated and its parameters are not fully observable the specified problem is not completely solved now and studies on the topic are still conducted.

The main features of the proposed approach are:

– usage of the operational data mining software to identify effective regions of the blast furnace technical parameters values, providing productivity increase and coke consumption reduction;

– real-time software for identification of the furnace cohesion zone current parameters for the operational management correction;

– forecasting of the blast furnace thermal state indicators dynamics when the blast parameters or charge load change.

1. The blast furnace control model general structure

The main difficulties preventing the achievement of high technical and economic efficiency levels are:

1) partial observability and controllability of processes;

2) the need for the processes stabilization in extreme boundary conditions;

3) incomplete knowledge about the current process state due to its complexity.

To overcome the above difficulties an advanced methodology of model predictive management is now developed. The peculiarity of this methodology comes from usage of controlled object modelling software with permanent on-line updating based on constant parameters identification by the real operational data for the observability and controllability of processes.

Therewith, each managing step solves the problem of control action on technical and economic indicators optimization.

The general structure of the model-predicative management is shown on Fig. 1.

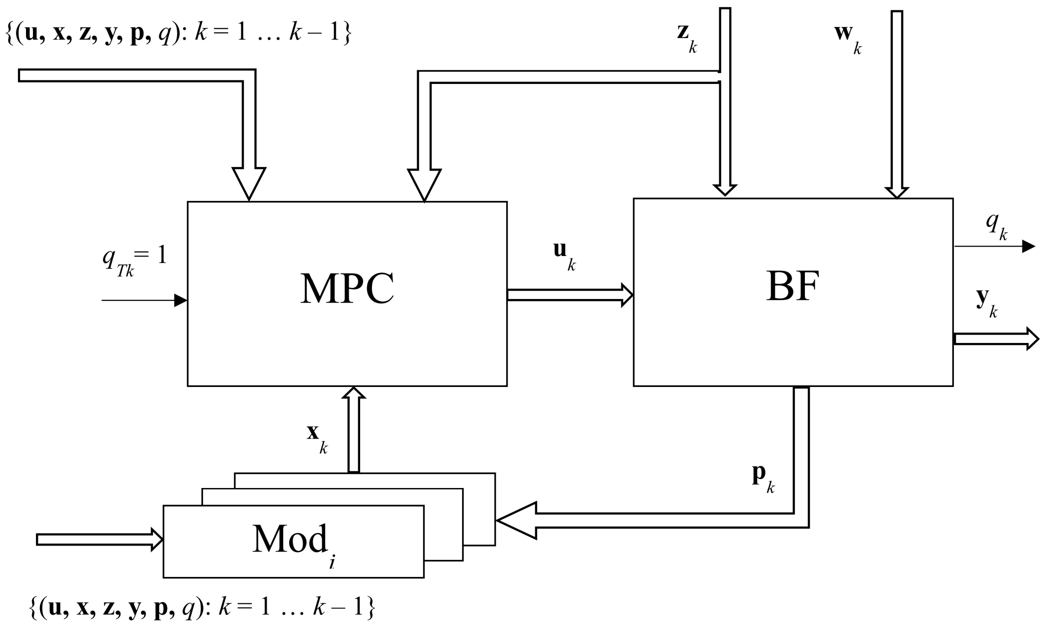

Fig. 1

Here in $\mathbf{u}_k$ – the controlled parameters of the blast furnace process (BFp); $\mathbf{z}_k$ – measured uncontrolled parameters of the BFp; $\mathbf{w}_k$ – unmeasured disturbance factors of the BFp; q_k – the blast furnace process efficiency indicator:

$$q_k = \begin{cases} 1, & \text{if BPf is satisfied with determined performance efficiency;} \\ 0, & \text{otherwise,} \end{cases}$$

$\mathbf{y}_k$ – the output measured parameters of the BFp; $\mathbf{x}_k$ – the blast furnace process state vector, for a satisfactory prediction of BFp characteristics; $\mathbf{p}_k$ – the measured parameters of the blast furnace process used to estimate its state vector; $\{(\mathbf{u}, \mathbf{x}, \mathbf{z}, \mathbf{y}, \mathbf{p}, q): k = 1 \ldots k-1\}$ – previous BF melting parameters statistics; $\mathbf{Mod}_i$ – the i-th model representation of the BFp, which provides state vector estimation according to technological instructions; **MPC** – the program of the model-predictive management calculation; k – the current melting index.

One BFp model representation for the state vector evaluation is the “AKOMM” Ltd. “Cohesion” system, which provides a quantitative assessment of the melting zone parameters.

2. Effective regions of the operating parameters clustering

The effective operating parameters regions are determined by the blast furnace target indicators settings, such as productivity, coke consumption, theoretical combustion temperature, furnace thermal state indicators (the cast iron silicon content, titanium module, blast-furnace gas utilization, etc.)

For instance, Fig. 2 represents effective region detection, based on the target function:

$$e_k = \alpha_n n_{ir} + \alpha_c b_c^{-1},\ \alpha_n,\ \alpha_c \geq 0,\ \alpha_n + \alpha_c = 1,$$

where n_{ir} – relative cast iron perfomance; b_c – the relative specific coke consumption; α_n, α_c – weights of partial indices n and c respectively as a part of a generalized target, reflecting the importance of performance and coke saving in the overall target structure.

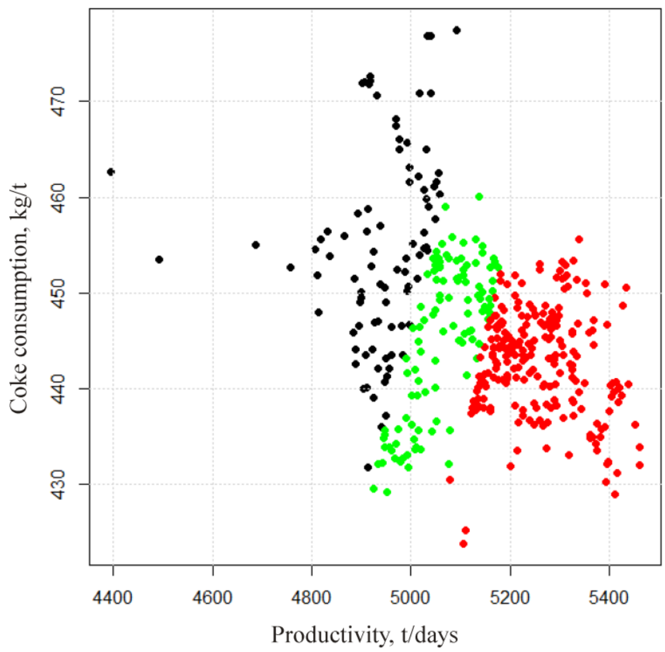

Fig. 2

Complexity of the considered effective region of operating parameters clustering task, in accordance with the division into target areas defined by specified levels of the target function (Fig. 2) caused due to is its high dimensionality. The number of operating parameters can be more than 70. To simplify the problem solution we used the method of exact area decomposition on the two-dimensional cross-section, analytically described by second order elliptical regions [42–43].

Fig. 3 represents an example of an increased efficiency area in the coordinates of the "specific coke consumption – cast iron silicon content" including furnace thermal state constraints.

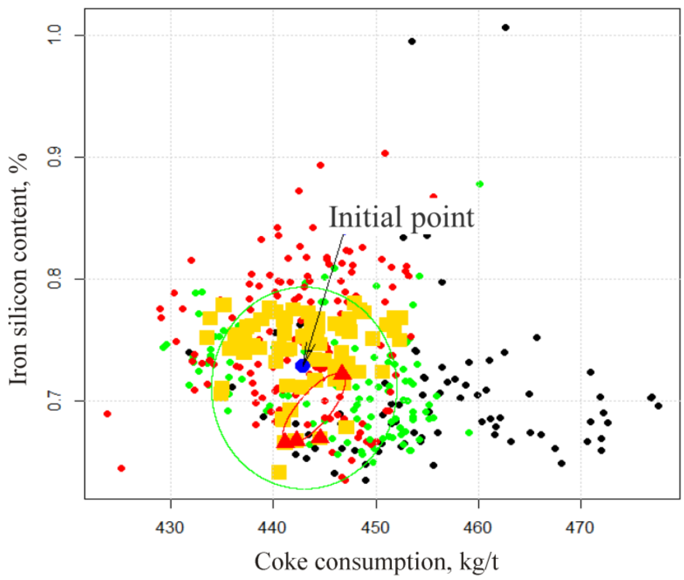

Fig. 3

The basic task of effective solutions definition lies in selecting the BF managed parameters $\{x_i : i \in I_m\}$ under the given unmanaged parameters constraints $\{x_i : i \in I_{unm}\}$. In general, the exact values of uncontrollable parameters are unknown and they are defined as areas of possible values. Managed and unmanaged (defined for operational control) parameters are shown in Tables 1 and 2, respectively.

Table 1

Managed parameters

	Parameter	Unit
$\{x_1 : i \in I_m\}$	The skip coke consumption (FR.+40) (abs)	kg/t
$\{x_2 : i \in I_m\}$	Blast moisture	t/м³
$\{x_3 : i \in I_m\}$	Natural gas consumption	м³/h

Table 2

Unmanaged parameters

	Parameter	Unit
$\{x_4 : i \in I_{unm}\}$	The hot blast oxygen content (only for fall)	%
$\{x_5 : i \in I_{unm}\}$	Sokolowski pellets charge share	shares
$\{x_6 : i \in I_{unm}\}$	Mickhailovski pellets charge share	shares
$\{x_7 : i \in I_{unm}\}$	Lebedinski pellets charge share	shares
$\{x_8 : i \in I_{unm}\}$	Kostomukshski pellets charge share	shares
$\{x_9 : i \in I_{unm}\}$	Kostomukshski non-flux pellets charge share	shares
$\{x_{10} : i \in I_{unm}\}$	Agglomerate share	shares

To solve this problem a quadratic solution residual of inequalities system is formulated:

$$E^2 = 0,5\sum_{i=1}^{n}\sum_{j=1}^{n}\left(\left(f_{ij}(x_i,\, x_j)\right)^+\right)^2, \quad (1)$$

$$\left(f_{ij}(x_i,\, x_j)\right)^+ = \begin{cases} f_{ij}(x_i,\, x_j), & \text{if } f_{ij}(x_i,\, x_j) > 0; \\ 0, & \text{if } f_{ij}(x_i,\, x_j) \le 0, \end{cases} \quad (2)$$

where f_{ij} – discriminant function analytically describing the effective region of the BF parameters.

The valid values of the parameters are restricted by inequalities:

$$x_i^{\min} \le x_i \le x_i^{\max}, \quad i \in I. \quad (3)$$

Quadratic constraints residual (3):

$$E_x^2 = 0,5\sum_{i=1}^{n}\left(\left(\left(-x_i + x_i^{\min}\right)^+\right)^2 + \left(\left(x_i - x_i^{\max}\right)^+\right)^2\right). \quad (4)$$

The residual of the solution (1) is based on the technological process monitoring statistics.

This statistics may be incomplete. In this case, the minimizing of solution residual problem formulation will be incorrect. We introduce the additional regularizing constraint to streamline problem formulation.

$$E_R^2 = 0,5\sum_{i=1}^{n}\left(x_i - x_{Ri}\right)^2. \quad (5)$$

Herein $\{x_{Ri}\}$ – valid values of operating parameters used for regularization; for example, the base parameters values obtained on the basis of technological calculations. Regularization usage is the central point of the approach proposed. Regularization allows generating consistent solutions based on both operating data and technological calculations.

The total residual of the inequalities solution (3) including constraints (5) is formulated as a penalty function:

$$E_0^2 = (1-\alpha)E^2 + \lambda E_x^2 + \alpha E_R^2. \quad (6)$$

The task is to find valid values of managed parameters by the criterion of minimum constraints residual (1) considering that the uncontrollable parameters within defined limits are streaming to provide the maximum of specified residual. This problem is a minimax mathematical programming problem:

$$\min_{\{x_i \in I_m\}} \max_{\{x_i \in I_{unm}\}} E^2(\{x_i : i \in I\}). \tag{7}$$

In general, the solution of the problem will be implemented by the gradient descent method. In this case, the recurrence algorithm for solving the problem would be as follows:

$$x_{i,k+1} = x_{i,k} - \gamma\left(\frac{\partial E^2}{\partial x_i} + \lambda\frac{\partial E_x^2}{\partial x_i} + \alpha\frac{\partial E_R^2}{\partial x_i}\right), \quad i \in I_m;$$

$$x_{i,k+1} = x_{i,k} - \gamma\left(-\frac{\partial E_{\text{св}}^2}{\partial x_i} + \lambda\frac{\partial E_x^2}{\partial x_i} + \alpha\frac{\partial E_R^2}{\partial x_i}\right), \; i \in I_{unm};$$

$$\frac{\partial E^2}{\partial x_i} = f_{ii}^+ \frac{y_i}{\sigma_i^2} + \sum_{\substack{j=1 \\ j\neq i}}^{n} f_{ij}^+\left(\frac{y_i}{\sigma_i^2} b_{ii}^{(11)} + \frac{y_j}{\sigma_j^2} b_{ji}^{(21)}\right) + \sum_{\substack{k=1 \\ k\neq i}}^{n} f_{ki}^+\left(\frac{y_k}{\sigma_k^2} b_{ki}^{(12)} + \frac{y_i}{\sigma_i^2} b_{ii}^{(22)}\right);$$

$$\frac{\partial E_x^2}{\partial x_i} = \left((-x_i + x_i^{\min})^+ + (x_i - x_i^{\max})^+\right);$$

$$\frac{\partial E_R^2}{\partial x_i} = x_i - x_{Ri}.$$

If the recurrent process converges, the result is a generalized solution of problem (7) under the given constraints.

For testing the BFp model-predictive control algorithms reporting forms are generated daily. They display BFp technological parameters of the current day, including the targets and factors of adaptive control. Based on reporting forms, a comparison is held between the actual values of factors influencing the BFp efficiency and an effective regime.

Developed algorithms based on the models produced in SCADA “PolyTER” are clarified to specify the area of high quality thermal state including the effective values of the current mode.

In addition, the approach for constructing the set of Pareto-optimal non-improvable solutions was implemented, when solving the blast furnace modes optimization problem.

The minimum coke consumption was used as the target function. Calculations were made for the following dependencies $P_i(C_c, W_{vapor})$, $\mathrm{Si}(W_{vapor})$, $M_{10}(W_{vapor})$, W_{vapor} when setting the desired BF operational mode, along with thermal state constraints considering different silicon content.

Fig. 4 represents the dependence between the optimal cast iron performance and coke quality (M_{10}). As we can see from the graph, cast iron performance increases while M_{10} falls, therewith decreasing the M_{10} productivity growth rate slows significantly. This is particularly evident when the values of M_{10} are close to a 8.0 and 8.2.

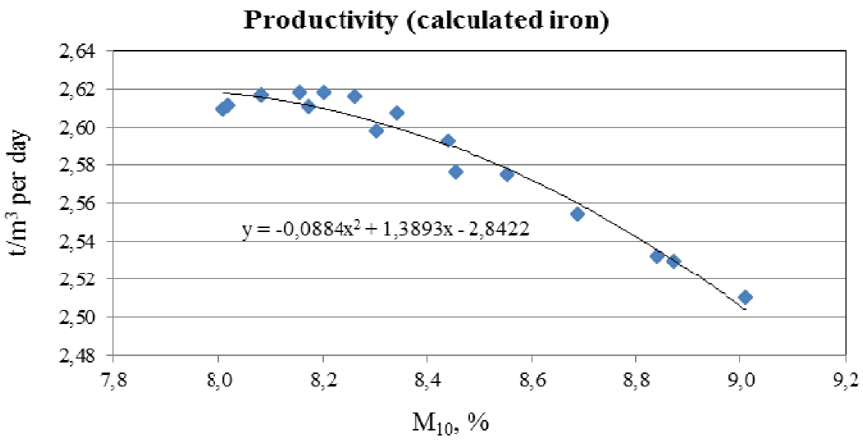

Fig. 4. Pareto region dependency between the cast iron performance andcoke quality (M_{10})

Fig. 5 shows the obtained dependency between the optimal values of coke consumption and coke quality (M_{10}). Decreasing the M_{10} leads to coke consumption decrease, however the significant deceleration of coke consumption rate is not observed, when reducing M_{10}.

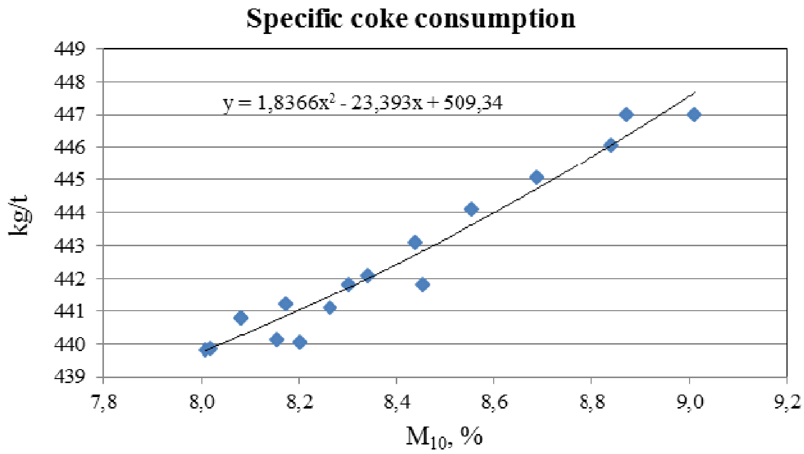

Fig. 5. Pareto region dependency between the coke consumption and coke quality (M_{10})

The dependencies, shown in Fig. 4–5, were built when processing statistical information for the period from 12.04.2014 to 07.02.2016, BF № 10 OJSC "MMK" excluding the downtime periods.

3. Operational BF real-time management

The solution of the BF operational management problem is implemented from point of view assuming the regime parameters dynamic stabilization in the defined increased effectiveness regions. The solution to this problem is very difficult, since the blast-furnace process as a controlled object has very complex properties:

1) BFp dynamics, taking long time intervals (up to 40 hours);
2) nonlinear nonstationary characteristics;
3) distributed parameters;
4) high level of disturbances;
5) low observability of many process characteristics.

4. Methods of operational management

To illustrate the operational management techniques we will consider the example of cast iron silicon content regulation via the channel of specific coke consumption influence (B_{coke}).

The transfer function between the cast iron silicon content (Si) and the specific coke consumption can be represented by two sequential dynamic delays: transport and inertial.

The transport delay estimation is based on calculating correlation function between the cast iron silicon content and B_{coke}. Correlation function maximum defines the value of transport delay. A recurrence relation describes the inertial delay:

$$\mathrm{Si}_k = a\mathrm{Si}_{k-1} + bB_{coke\,k}, \qquad (8)$$

where a, b – unknown coefficients, identified on current operational data; k – current time.

Identification of the a, b coefficients is carried out with synchronized real time operational silicon and B_{coke} data.

For silicon level regulating using the recurrent formula (8) necessary correction of the coke flow is calculated to achieve the required level of the cast iron silicon content. The required amount of silicon content is set through the previously discussed optimization problem based on the usage of efficient BF mode clusters.

For instance, Fig. 6 represents an example of silicon level regulation in an operational environment of SCADA "PolyTER".

Currently implemented operational management uses the following parameters:the cast ironsilicon content, iron temperature,titanium module, furnace shaft temperature, furnacehearth temperature.

The framework of SCADA "PolyTER" is displayed in Fig. 7.

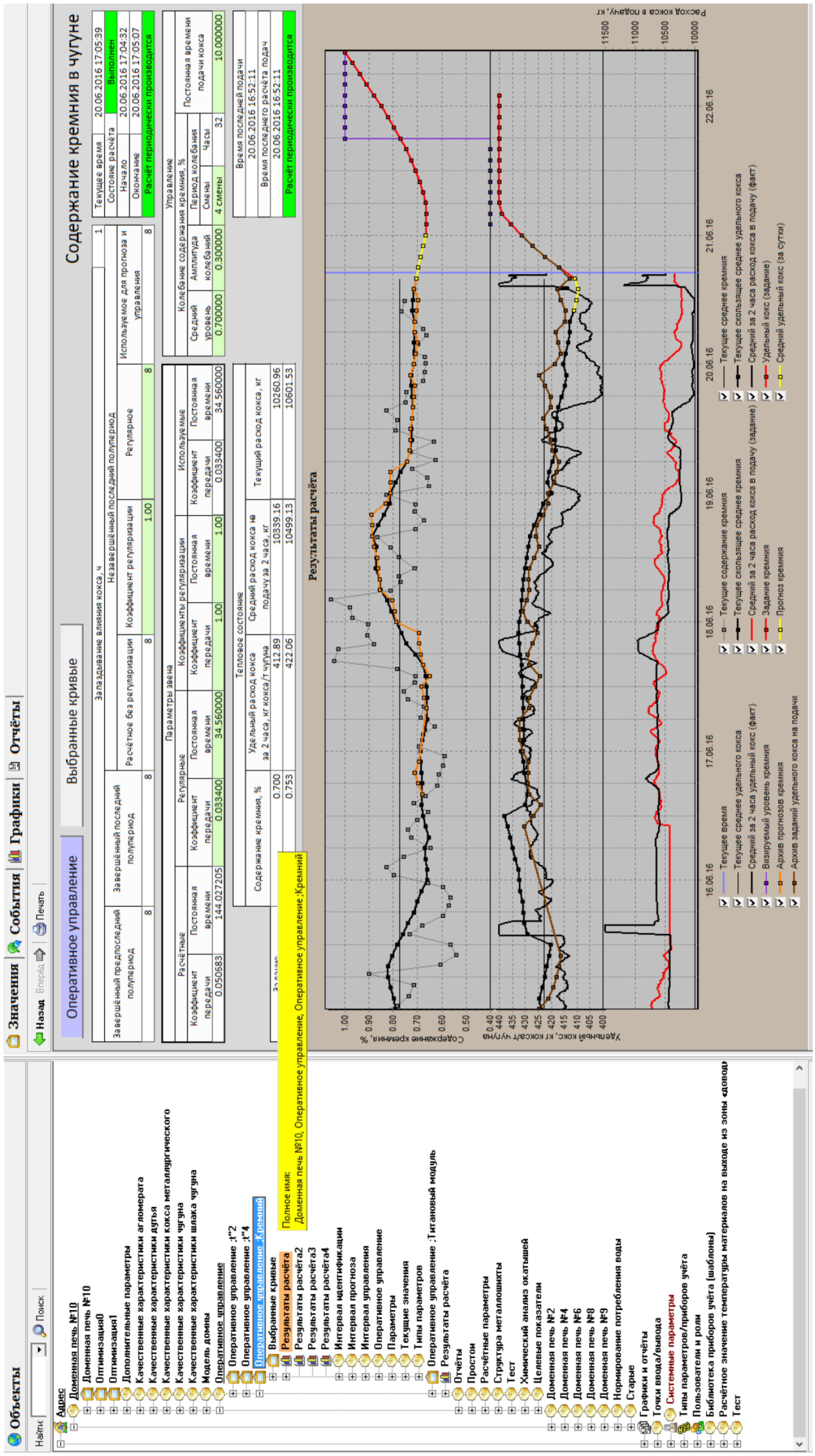

Fig. 6. Screen form of BF operational management settings page (cast iron silicon content example)

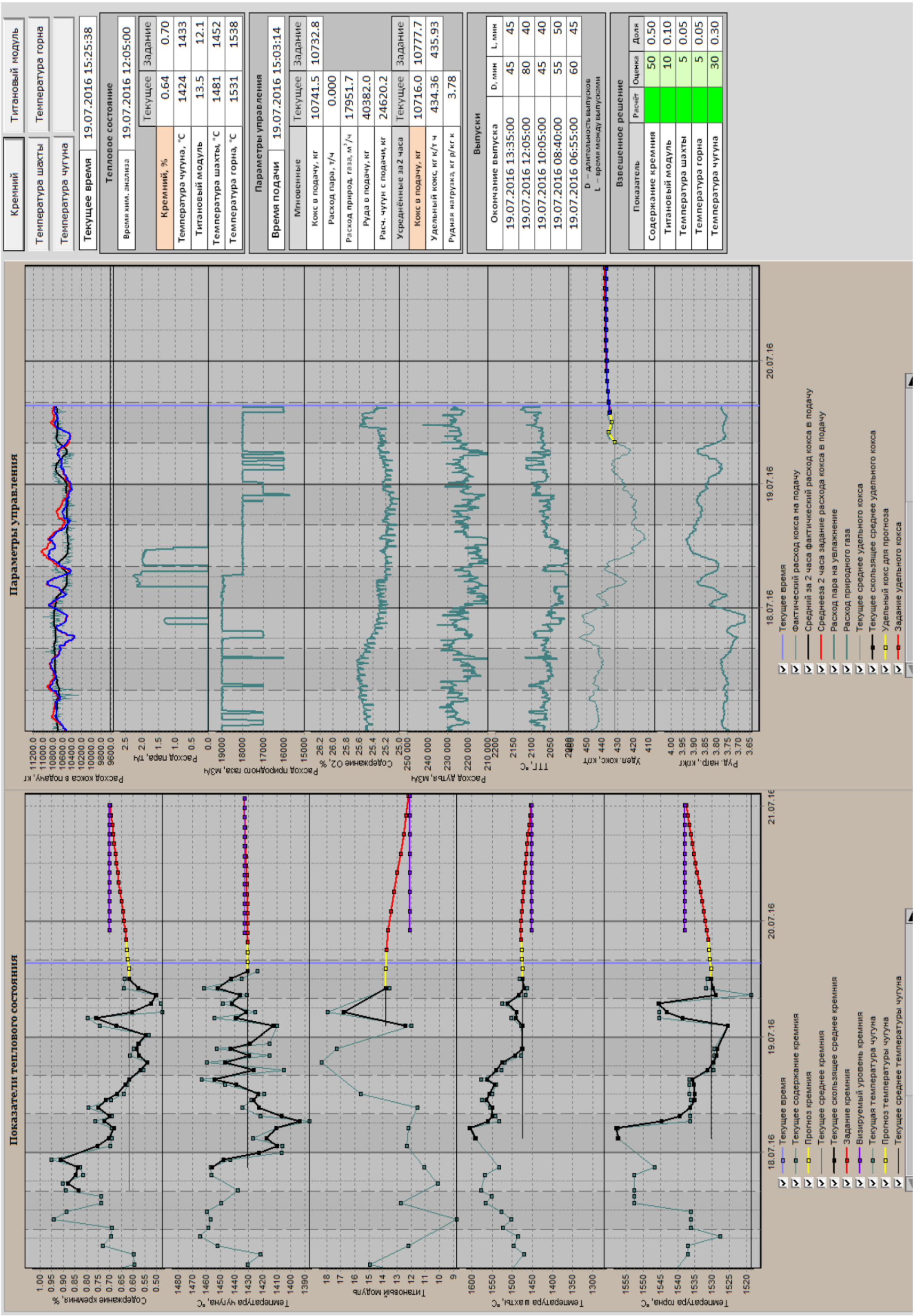

Fig. 7. The framework of a SCADA “PolyTER”

The left part of the diagram shows the graphs of the BF thermal state indicators: cast iron silicon content, titanium module, furnace shaft temperature and furnace hearth temperature. Here each indicator matches its current value (gray-green color), filtered current values (black color), forecast values (yellow color), target values (red color) and its visual level (purple color).

The middle part of the graphs shows current values of the controlled parameters: steam consumption for humidification, natural gas consumption, oxygen content in the blast, theoretical combustion temperature, and control parameters values 2-hour averaged: coke consumption per feeding, specific coke consumption per ton of calculated iron, ore load. Moreover, system displays job graphs for the specific coke consumption:

1) defined according to the desired value of the cast iron silicon content (red line);

2) based on weighted decision (blue line). Weighted decision is using specific coke tasks defined by the required values of the BF thermal state indicators.

Coke consumption per feeding considering cast iron per feeding is counted through the framework charts of specific coke consumption.

Conclusion

1. To improve the blast furnace process efficiency we propose a model predictive control approach, based on clustering of blast furnace process effective parameters values regions and operational parameters stabilization within an efficient cluster using the forecast based on their dynamics.

2. We introduce method of multidimensional blast furnace effective parameters values regions decomposition using two-dimensional cross-sections and their analytical representation based on second order elliptic regions.

3. We provide the algorithmic solution for the optimal choice of blast furnace process controlled parameters with uncontrollable parameters possible variations using the multidimensional effective parameters values regions.

4. It is shown that using Pareto regions in the blast furnace process parameters coordinates, derived from the optimization problem solution, allows to assess the potential boundaries of high performance efficiency depending on the operating parameters. The obtained dependences can be used for technological calculations of the mode parameters estimating potential attainability of the effective values.

5. Blast furnace process regime parameters stabilization should be carried out based on predicting of their values using models of the dynamics. The real time dynamic models parameters identification algorithms are developed.

6. The automated blast furnace process decision support system was developed based on the methodical and algorithmic maintenance, implemented in SCADA “PolyTER”.

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АВТОМАТИЗАЦИЯ ОПЕРАТИВНОГО УПРАВЛЕНИЯ ДОМЕННЫМ ПРОЦЕССОМ С ИСПОЛЬЗОВАНИЕМ МОДЕЛЬНО-УПРЕЖДАЮЩЕГО ПОДХОДА

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Рассматривается задача автоматизации оперативного управления доменным процессом с использованием методов, основанных на моделировании и выработке упреждающих решений в реальном времени on-line с объектом управления. Характерными особенностями создаваемой системы оперативного управления являются:

– использование программных средств интеллектуального анализа данных эксплуатации для выявления эффективных областей значений режимных параметров печи;

– наличие программы идентификации в реальном времени текущих параметров зоны когезии доменного процесса для коррекции оперативного управления;

– прогнозирование динамики изменения индикаторов теплового состояния печи при изменениях параметров дутья и загрузки шихтовых материалов.

В результате применения указанных программных средств достигается выведение режимных параметров доменного процесса в эффективную область значений повышенной производительности и снижение потребления кокса при значительных изменениях исходных параметров шихты, которые обусловлены использованием шихтовых материалов от разных поставщиков. При этом прогнозирование динамики режимных параметров позволяет мастеру стабилизировать доменный процесс в эффективной области их значений.

Система реализуется в рамках совместной разработки Южно-Уральского государственного университета (национального исследовательского университета) (Челябинск), ООО НПП «Политех-Автоматика» (Челябинск) и ООО «АКОММ» (Москва).

Ключевые слова: доменный процесс, модельно-упреждающее управление.

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