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Expert System for Sintering Process Control based on the Information about solid-fuel Flow Composition

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***Abstract*—**Usually, the solid-fuel flow of an iron ore sinter plant consists of different types of the solid-fuels, which differ from each other. Information about the composition of the solid-fuel flow usually comes every 8-24 hours. It can be clearly seen that this information cannot be used to control the sintering process in real time. Due to this, we propose an expert system which uses indirect measurements from the process in order to obtain the composition of the solid-fuel flow by solving an optimization task. Then this information can be used to control the sintering process. The proposed technique can be successfully used to improve sinter quality and reduce the amount of solid-fuel used by the process.

***Keywords*—**sintering process, particle swarm optimization, optimal control, expert system, solid-fuel

I. INTRODUCTION

IN order to prove the necessity of development of our expert system, we start this article with a brief review of existing solutions. Many researchers proposed different techniques to control the sintering process. The paper [1] describes the model based control system of the sintering process. The control includes ignition control, sintering control and exhaustion control. The mathematical models are derived from basic models of physical and chemical processes and use directly and indirectly measured quantities from sintering strand. The control system determines the optimal quantity of coke, volume of coke combustion air, preheating gas volume, combustion air for preheating and volume of exhausted gases. The values of these quantities are corrected according to the identified process state. Manipulated variable is the turbo-exhausters operating speed. In article [2], in order to solve air leakage of sintering testing cumbersome, inaccurate results, and other issues, the sinter machine air leakage characteristics were studied, combining the mathematical modeling and the field detection. Air leakage location diagnosis expert system was established to judge specific air leakage locations.

Authors Dai-fei L., Xu-ling C. [3], in order to obtain optimal process parameters for sintering process, developed a data mining system that mainly including the process parameters module, the data mining module, the process diagnosis module, the human-machine and data interface.

By integrating fuzzy cluster analysis, time series and artificial neural network technology, the system can deduce optimal information from complex production data, and realize four kinds of analysis that include sinter chemical composition analysis, sintering process state analysis, energy consumption analysis and state diagnosis.

In 2010 Xu-ling C., Xiao-hui F., Tao J. proposed an operation guidance system for iron ore sintering process. The system was developed, according to the characters of sintering plant in China. The sintering process is divided into three stages that forming, moving and disappearing of reaction zone. The control strategy integrated soft measurement, prediction and fuzzy control technology was put forward on the basis of analysis to mechanism of sintering process [4]. In work [5] an intelligent integrated optimization algorithm based on comprehensive production Indices is presented to solve the optimization control problem of comprehensive production Indices. First, the neural network prediction model for the comprehensive production indices is proposed, which is synthesizing a lot of techniques, including correlation analysis, principal components analysis, and neural network and so on. And the target function was deduced using the multi-objective satisfactory optimization technology. The results of actual runs show that the proposed intelligent integrated algorithm provides a efficient and applied way to resolve the problem of optimization control for the complex strong correlation coupling, time-varying delay industrial process, and provides an effective and new idea to implement the global optimization control for process industry.

Langer M. [6] proposed a hybrid modeling method combined with a suitable classification of process characteristics which ensures a widespread model synthesis for quality prediction based on the fuzzy neural network. Many other systems were actually developed [7, 8, 9].

The works that were previously described didn't consider problems related to the solid-fuel flow composition. However, our experience shows that the problem of fluctuating solid-fuel flow composition is widely spread at major Russian sinter plants. The actual problem can be described as follows: the solid-fuel flow usually consists of several types of fuels, and these types are different (in terms of the chemical composition). Because of this an operator should correct the consumption of the solid-fuel flow whenever the ratios between different types of the fuels have been changed. The problem is that the information about these ratios as well as the information about the chemical composition of the solid-fuel flow is gathered only every 8-24 hours and thus cannot be used to real time control of the sintering process.

In this article, we describe an expert system for control of an iron ore sintering process by means of the solid-fuel composition reconstruction from indirect measures of the sintering process.

II. CASE STUDY

In this section, we consider the problem of the solid-fuel flow composition by the example of Magnitogorsk Metallurgical Combine (MMC) sintering plant. At the MMC,

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the solid-fuel flow consists of three types of solid-fuels, which differ from each other. Information about the composition of the solid-fuel flow usually comes every 8 hours. In the fig. 1, you can see how these types of solid-fuels fluctuate. Some of the solid-fuel types have higher heat of combustion than others. This actually means that if more calorific fuel is replaced by less calorific, an operator should increase the solid-fuel consumption drastically in order to produce the sinter of proper quality.

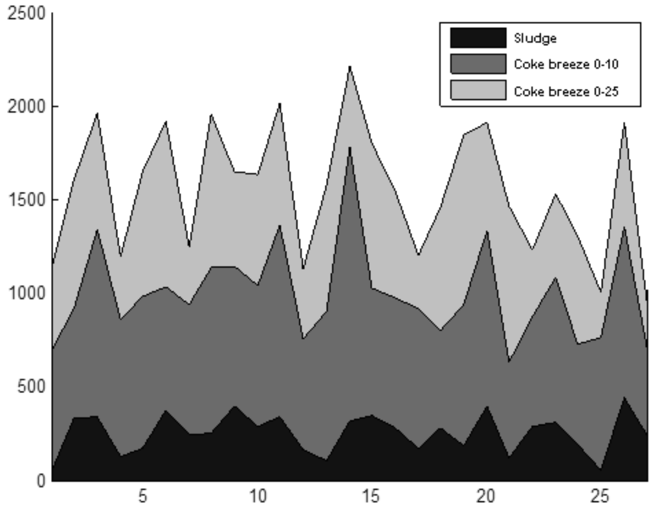

Fig. 1 Fluctuations of the solid-fuel types at MMC (every 8 hours)

Statistical analysis was carried out in order to get information about general statistical characteristics as standard deviation and mean. The results are summarized in tables I and II.

TABLE I
RESULTS OF A STATISTICAL ANALYSIS OF THE SOLID-FUEL FLOW USED BY MMC

Solid fuel type	Minimum	Maximum	Expected value	Standard deviation
Sludge, %	5.07	25.89	16.09	5.76
Coke breeze 0-10, %	34.39	70.24	48.50	9.31
Coke breeze BF 0-25, %	19.59	56.98	35.39	9.17

TABLE II
RESULTS OF A STATISTICAL ANALYSIS OF THE RATIOS OF THE DIFFERENT SOLID-FUEL TYPES USED BY MMC

Solid fuel ratio	Minimum	Maximum	Expected value	Standard deviation
Sludge/Coke breeze 0-10	0.07	0.56	0.34	0.14
Sludge/Coke breeze BF 0-25	0.13	1.02	0.49	0.23
Coke breeze 0-10/Coke breeze BF 0-25	0.60	3.37	1.52	0.68

It can be seen that the solid-fuel flow consists of three types: sludge, coke breeze 0-10 and coke breeze BF 0-25 (coke breeze from the blast furnace). Coke breeze BF 0-25 is the most calorific, and if it should be replaced by coke breeze 0-10, an operator should increase the consumption of the solid-fuel flow.

From the analysis, it is seen that the composition of the solid-fuel flow fluctuates sufficiently. This can lead to decreasing quality of the sinter. Thus, development of the expert system which will be able to reconstruct the solid-fuel flow composition by means of indirect measures is the urgent problem.

III. RECONSTRUCTION OF THE SOLID-FUEL FLOW COMPOSITION

In this section we will describe a technique which can be used to reconstruct the solid-fuel flow composition by indirect measures of the process.

This technique is based on the fact that we know some information about the process, the solid-fuel composition ratios (expected values) and the chemical composition of the different solid-fuel types. For example, in the table III, we present the average chemical composition of the solid-fuel types used by MMC.

TABLE III
AVERAGE CHEMICAL COMPOSITION OF THE SOLID-FUEL TYPES USED BY MMC

Solid-fuel type	Moisture, W	Ash, A	Volatile, V	Sulfur, S	Carbon, C
Sludge	4,12	17,74	2,01	0,47	75,66
Coke breeze 0-10	3,13	13,09	1,55	0,46	81,76
Coke breeze 0-25	2,04	12,94	1,37	0,46	83,20

Based on this information and the information about the current chemical composition of the solid-fuel flow, we can write the set of balance equations and estimate the difference or error between the current values and the expected values.

First of all, we write some balance equations for ash, volatile, moisture, granulometric composition and sulfur for our solid-fuel flow.

The ash balance equation of the solid-fuel flow can be written in the following way:

$$\Omega^A = (A_K^{\Sigma} - A_K^{*}) = A_K^{\tau} - \frac{\sum_{j=1}^{m} A_j^i \cdot Q_j^i}{\sum_{j=1}^{m} Q_j^i}, \qquad (1)$$

where i is some discrete moment of time, τ is some discrete moment of time where the last chemical analysis of the solid-fuel flow was gathered, A_j^i is the content of ash in the solid-fuel of some type j, Q_j^i is the consumption of the solid-fuel of some type j and A_K^{τ} is the ash content of the solid-fuel flow.

The value of Ω^A is the difference between the expected content of ash in the solid-fuel flow estimated by the balance equation (based on the information about solid-fuel types) and the current content of ash in the solid-fuel flow (we use the last chemical analysis of the solid-fuel flow).

Similarly, we can write the difference for the granulometric composition of the solid-fuel flow:

$$\Omega^D = (D_K^\Sigma - D_K^*) = D_K^\tau - \frac{\sum_{j=1}^{m} D_j^i \cdot Q_j^i}{\sum_{j=1}^{m} Q_j^i}. \qquad (2)$$

The volatile balance equation of the solid-fuel flow can be written in the following way:

$$\Omega^V = (V_K^\Sigma - V_K^*) = V_K^\tau - \frac{\sum_{j=1}^{m} V_j^i \cdot Q_j^i}{\sum_{j=1}^{m} Q_j^i}. \qquad (3)$$

The difference for the sulfur content of the solid-fuel flow can be written:

$$\Omega^S = (S_K^\Sigma - S_K^*) = S_K^\tau - \frac{\sum_{j=1}^{m} S_j^i \cdot Q_j^i}{\sum_{j=1}^{m} Q_j^i}. \qquad (4)$$

The moisture of the solid-fuel composition can be estimated by the following equation:

$$\Omega^W = (W_K^\Sigma - W_K^*) = W_K^\tau - \frac{\sum_{j=1}^{m} W_j^i \cdot Q_j^i}{\sum_{j=1}^{m} Q_j^i}. \qquad (5)$$

The error for the FeO content of the solid-fuel flow can be calculated in this way:

$$\Omega^{FeO} = (FeO_K^\Sigma - FeO_K^*) = FeO_K^\tau - \frac{\sum_{j=1}^{m} FeO_j^i \cdot Q_j^i}{\sum_{j=1}^{m} Q_j^i}. \qquad (6)$$

Using the balance equation for basicity of the mix material, we can take into account the content of CaO and SiO_2 in the solid-fuel flow and the solid-fuel types:

$$\Omega^M = (M_K^\Sigma - M_K^*) = \frac{Q_K^i \cdot (100 - W_K^\tau / 100) \cdot \frac{(CaO)_K^\tau}{100}}{Q_K^i \cdot (100 - W_K^\tau / 100) \cdot \frac{(SiO_2)_K^\tau}{100}} - \frac{\sum_{j=1}^{m} Q_{jK}^i \cdot (100 - W_j / 100) \cdot \frac{(CaO)_{jK}^i}{100}}{\sum_{j=1}^{m} Q_{jK}^i \cdot (100 - W_j / 100) \cdot \frac{(SiO_2)_{jK}^i}{100}}. \qquad (7)$$

Further on, for the sake of simplicity, we will omit indices i and τ.

The next step is to take into account some differences which are related to the content of FeO in the sinter. These differences can be calculated using information about reduction-oxidation reactions [10].

In order to obtain the information about reduction-oxidation reactions we should find the ratio $\left(CO/CO_2\right)^P$ of the combustion products. But we can only measure $\left(CO/CO_2\right)^G$ of the sintering gas. We will use a technique which was proposed in [10] to find $\left(CO/CO_2\right)^P$ from the chemical analysis of the sintering gas.

First of all, we should make some corrections to the chemical analysis of the sintering gas because the sample contains some water steam in it.

The amount of oxygen and nitrogen in the humid air can be calculated as follows:

$$A = O_2 + N_2 = 100 - H_2O^A. \qquad (8)$$

The content of the saturated water steam in gas can be obtained:

$$H_2O^A = (P^{H_2O} / P_0) \cdot 100. \qquad (9)$$

Where P^{H_2O} can be calculated from the equation:

$$P^{H_2O} = P_{SAT}^{t=env} \cdot \phi_{AIR}{}^{t=env}, kPa, \qquad (10)$$

where $\phi_{AIR}{}^{t=env}$ is the humidity of air with the current temperature and $P_{SAT}^{t=env}$ is the saturated water vapor pressure with the current temperature.

The overall atmospheric pressure:

$$P_0 = 101{,}3 \cdot P^{ATM} / P^{ATM.NC}, \qquad (11)$$

where P^{ATM} is the current atmospheric pressure and $P^{ATM.NC}$ is the atmospheric pressure at normal conditions.

Then content of oxygen and nitrogen in the humid air can be estimated:

$$\begin{aligned} O_2 &= 21 \cdot A, \%, \\ N_2 &= 79 \cdot A, \%. \end{aligned} \qquad (12)$$

The content of water steam and hydrogen of the sintering gas can be calculated as follows:

$$H_2O^G + H_2^G = \frac{H_2O^A}{(V^G / V^A)}. \qquad (13)$$

From the expression (13), we can calculate the value of H_2O^G, given the value of H_2^G. Where H_2^G is the amount of hydrogen, which appears as a result of water steam decomposition and V^G, V^A are specific volumes of the sintering gas and the air that is used by the sintering process accordingly.

So, the amount of saturated water steam in our gas sample can be obtained in this way:

$$\begin{aligned} H_2O_{SAT}^G &= (P^{H_2O} / P_0) \cdot 100, \\ P^{H_2O} &= P_{SAT}^{t=env}, kPa. \end{aligned} \qquad (14)$$

Finally, we can estimate the amount of water steam which comes from the wet mix material:

$$\begin{aligned} H_2O^{*G*} &= H_2O^G - H_2^G, \\ H_2O^{MIX} &= H_2O_{SAT}^G - H_2O^{*G*}. \end{aligned} \qquad (15)$$

The relative volume of the combustion products and the gas sample:

$$\psi_{CP} = 100 - H_2O^{MIX}. \tag{16}$$

Thus, the actual content of O_2, CO, CO_2 in the sintering gas will be more than in the gas sample by ψ_{CP}:

$$\begin{aligned} &O_2^G = O_2 / \psi_{CP}, \\ &CO^G = CO / \psi_{CP}, \\ &CO_2^G = CO_2 / \psi_{CP}, \\ &N_2^G = 100 - (O_2^G + CO^G + CO_2^G + H_2O^{*G*} + H_2^G). \end{aligned} \tag{17}$$

The total content of carbon of the solid-fuel flow in the mix material:

$$\begin{aligned} C_{MIX} &= C_{FUEL}^{CARB.} \cdot Q_{MIX}^K, \\ Q_{MIX}^K &= \frac{Q^K}{\sum_{j=1}^{N} Q_j}. \end{aligned} \tag{18}$$

The amount of carbon of the solid-fuel flow can be represented as a sum:

$$C_{FUEL}^{CARB.} = \frac{\sum_{j=1}^{m} C_j^{CARB.} \cdot Q_j^K}{\sum_{j=1}^{m} Q_j^K}, \tag{19}$$

where $C_j^{CARB.}$ is the content of carbon in the solid-fuel of a type j and Q_j^K is the consumption of the solid-fuel of a type j.

The total content of carbon of the fluxes in the mix material:

$$\begin{aligned} C^F &= Q_{MIX}^{FLUX} \cdot CaO \cdot \frac{12}{56}, \%, \\ Q_{MIX}^{FLUX} &= \frac{Q^{FLUX}}{\sum_{j=1}^{N} Q_j}. \end{aligned} \tag{20}$$

The combustion of the mix material carbon in the humid air can be written as follows:

$$\begin{aligned} &C + \delta k(O_2 + \gamma N_2 + rH_2O) + \beta CO_2' = \\ &= 2(1-k)CO + (2k-1)CO_2 + \\ &+ k(\delta - 1)O_2 + \delta k \gamma N_2 + \delta k r H_2O + \beta CO_2', \end{aligned} \tag{21}$$

$$\sum M = 1 + \beta + k[\delta(1 + \gamma + r) - 1], \tag{22}$$

$$k = \frac{1+\beta}{\frac{100\delta\gamma}{N_2^G} - [\delta(1+\gamma+r) - 1]}. \tag{23}$$

Then, the amount of CO and CO_2 in the combustion products we will obtain using these equations:

$$CO = \frac{2(1-k)100}{\sum M}, \tag{24}$$

$$CO_2 = \frac{2(2k-1)100}{\sum M}, \tag{25}$$

$$O_2 = \frac{k(\delta - 1)100}{\sum M}, \tag{26}$$

$$N_2 = \frac{\delta k \gamma 100}{\sum M}, \tag{27}$$

$$\delta = \frac{N_2^G}{N_2^G - \gamma O_2^G}, \tag{28}$$

where γ is the ratio of nitrogen moles to oxygen moles which are utilized by the combustion reaction of carbon:

$$\gamma = \frac{N_2^A}{O_2^A - \Delta O} = \frac{79\%}{21\% - \Delta O\%}, \tag{29}$$

where ΔO is the amount of oxygen which is spent on oxidation of the mix material FeO in the upper part of the mix material cake.

Coefficient k determines the ratio $CO : CO_2 = m / n$. And coefficients m and n:

$$m = 2(1-k), \tag{30}$$

$$n = 2k - 1. \tag{31}$$

Other coefficient can be calculated from the following equations:

$$\beta = C^F / C^{MIX}, \tag{32}$$

$$r = \frac{H_2O^A}{O_2^A - \Delta O}. \tag{33}$$

Authors [10] noted that there is a serious problem with the parameter ΔO which should be selected in order to carry out these calculations. If this parameter is selected incorrectly this will lead to the wrong results. We will discuss how to find this parameter later on.

In general the technique which we have discussed can be used to estimate the theoretical content of the combustion products by indirect measures (chemical analysis of the sintering gas).

Based on this information, we should continue our calculations in order to find the value of FeO of the sinter. For this reason, we will use formulae to calculate oxidation-reduction reactions.

The first stage is to find the amount of FeO which appears during the reduction process. This amount can be obtained using the equation:

$$\Delta CO = CO^{CP} - CO_{H_2O} - CO^G, \%, \tag{34}$$

where CO_{H_2O} is the amount of CO, which is spent on the decomposition of the water steam, CO^{CP} is the content of CO in the combustion products, CO^G is the content of CO in the sintering gas.

The amount of CO_{H_2O} is equal to H_2^G, H_2^G is the amount of hydrogen which appears as a result of the water steam decomposition:

$$\Delta CO = CO^{CP} - H_2^G - CO^G, \%. \tag{35}$$

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The computational equation which can be used to estimate the amount of FeO which appears during the reduction process:

$$+\delta FeO = 0.12 \cdot \Delta CO \cdot \sum M \cdot C^{MIX}, \%, \qquad (36)$$

where $\sum M$ is the amount of moles of the combustion products per one mole of carbon; C^{MIX} is the total content of carbon of the solid-fuel flow in the mix material, %.

The computational equation which can be used to estimate the amount of FeO which disappears during the oxidation process:

$$-\delta FeO = 0.24 \cdot \Delta O \cdot \sum M_A \cdot C^{MIX}, \%, \qquad (37)$$

where $\sum M_A = \delta k(1 + r + \gamma)$ is the amount of moles of the humid air using by the reaction per one mole of carbon.

Thus, if the content of FeO in the mix material is FeO^{MIX} then the content of FeO in the sinter can be written:

$$FeO^{SF} = FeO^{MIX} + \delta FeO - \delta FeO. \qquad (38)$$

Because the mass of the sinter is less than the mass of the dry mix material (due to the fact that during the sintering process the amount of carbon, sulfur, CO_2, $CaCO_3$ and some other components is reduced). The actual content of FeO in the sinter will be:

$$FeO^{SNT} = FeO^{SF} \cdot \zeta, \qquad (39)$$

where ζ characterizes the losses of the mass of the mix material during the sintering process and it can be obtained from the expression [11]:

$$\zeta = Q^{SINTER} / Q^{DRY\,MIX}, \qquad (40)$$

$$Q^{DRY\,MIX} = ((1 - W_{MIX}) / 100) \cdot Q^{MIX}. \qquad (41)$$

Finally, we can calculate differences which are related to the content of k in the sinter:

$$\begin{aligned} \Omega^{FeO\,SNT} &= (FeO)^{SNT} - (FeO)^{SNT\wedge}, \\ \Omega^{CO} &= (CO - CO^{\wedge}), \\ \Omega^{CO_2} &= (CO_2 - CO_2^{\wedge}). \end{aligned} \qquad (42)$$

As we stated before, the problem of this method is that we should select the value of ΔO and H_2^G. In this article we propose to solve an optimization task in order to find the values of these parameters.

For this reason, we built neuro-fuzzy model which can be used to forecast the content of FeO in the sinter. We selected the following structure of our model:

$$FeO^{SNT} = f(FeO^{MIX}, FeO^{SNT}_{t-\tau}, FeO^{MIX}_{t-24}, C^{MIX}, M^{MIX}), \qquad (43)$$

where FeO^{MIX} is the content of FeO in the mix material, $FeO^{SNT}_{t-\tau}$ is the content of FeO in the previous chemical analysis of the sinter, FeO^{MIX}_{t-24} is the content of FeO in the mix material shifted in time, M^{MIX} is the basicity of the mix material.

The detailed information about how to construct neural-fuzzy models can be found in [12]. Then, in order to find unknown parameters we should solve the following optimization problem:

$$F(\Omega) = \left(FeO^{SNT} - FeO^{SNT}_{ANFIS}\right)^2 \to \min, \qquad (44)$$

where FeO^{SNT} is the content of FeO in the sinter which is calculated by the formula (39) and FeO^{SNT}_{ANFIS} is the forecast of FeO in the sinter, which is calculated using adaptive neuro-fuzzy inference system (ANFIS).

This problem should be solved taking into account the following constraints:

$$\begin{cases} \Delta O \geq 0 \\ H_2^G \geq 0 \end{cases}. \qquad (45)$$

The solution to this problem will be the values for ΔO and H_2^G, which then can be used to calculate the differences $\Omega^{FeO\,SNT}$, Ω^{CO}, Ω^{CO_2}.

Using heat balance equations we can get some other differences which then will be used together.

The heat of combustion of carbon can be determined as follows ($kJ / N, kg$):

$$Q_C = \{X_{CO_2} \cdot 33355 + (1 - X_{CO_2}) \cdot 9780\} \cdot C_K^{CARB.}, \qquad (46)$$

where X_{CO_2} is the part of carbon which is burned to CO_2, and it can be determined from this equation:

$$X_{CO_2} = \frac{CO_2^{CP}}{CO_2^{CP} + CO}. \qquad (47)$$

Then, the difference can be written as follows:

$$\begin{aligned} \Omega^{QC} &= (Q_C - \hat{Q}_C) = \\ &= \{X_{CO_2} \cdot 33355 + (1 - X_{CO_2}) \cdot 9780\} \cdot C_K^{CARB.} - \\ &- \sum_{j=1}^{m} \{\hat{X}_{CO_2} \cdot Q_j^{CO_2} + (1 - \hat{X}_{CO_2}) \cdot Q_j^{CO}\} \cdot C_K^{CARB.j}. \end{aligned} \qquad (48)$$

The heat of the air Q_A, which is brought to the sinter strand, can be calculated in the following way:

Specific volume of the sintering gas:

$$V_\Gamma = 1,867 \frac{C_{MIX}\,\% + C_F\,\%}{CO_2^G\,\% + CO^G\,\%}. \qquad (49)$$

Specific volume of the air can be calculated using specific volume of the sintering gas as follows:

$$\begin{aligned} N_2^G &= 100 - (O_2^G + CO^G + CO_2^G + H_2O^{*G*} + H_2^G), \\ A &= 100 - H_2O^A, \\ N_2^A &= 79 \cdot A, \%, \\ V_A &= V_G \cdot \left(N_2^G, \% \middle/ N_2^A, \%\right), m^3 / kg\ of\ dry\ mix. \end{aligned} \qquad (50)$$

Finally, we can get the enthalpy of the air:

$$Q_A = V_A(m^3 / kg\, of\ dry\, mix) \cdot Q_{MIX} \cdot \\ \cdot c_A^t (kJ / kg \cdot {}^\circ C) \cdot t_A({}^\circ C), kJ / Q\, kg. \tag{51}$$

The difference will be calculated using this expression:

$$\hat{\Omega}^{AIR} = (Q_A - \hat{Q}_A) = V_A \cdot Q_{MIX} \cdot c_A^t \cdot t_A - \\ -\hat{V}_A \cdot \hat{Q}_{MIX} \cdot c_A^t \cdot t_A = c_A^t \cdot t_A \cdot (V_A \cdot Q_{MIX} - \hat{V}_A \cdot \hat{Q}_{MIX}). \tag{52}$$

We can simplify this expression by dividing it by $c_A^t \cdot t_A$:

$$\Omega^{AIR} = (Q_A - \hat{Q}_A) = (V_A \cdot Q_{MIX} - \hat{V}_A \cdot \hat{Q}_{MIX}). \tag{53}$$

The heat of the reduction or oxidation reaction can be determined by this formula:

$$Q_{OR} = k \cdot \{FeO_{MIX} - FeO_{SNT}\} \cdot Q_{MIX}, \tag{54}$$

where k is the heat which is consumed or received during the reduction or oxidation reaction and it is equal to $2028\, kJ / kg$.

Then we can calculate the following difference in order to take into account the nonlinear dependency:

$$\widehat{\Omega}^{OR\,FeO} = Q_{OR} - \hat{Q}_{OR} = k \cdot \{FeO_{MIX} - FeO_{SNT}\} \cdot Q_{MIX} - \\ -k \cdot \{FeO_{MIX} - FeO^*_{SNT}\} \cdot Q^*_{MIX}. \tag{55}$$

Taking into account this expression:

$$Q^*_{MIX} = \sum_{j=1}^{N-1} Q^j + \sum_{j=1}^{m} Q_K^j, \\ Q_{MIX} = \sum_{j=1}^{N-1} Q^j + Q_K. \tag{56}$$

And the expression for the consumption of the solid-fuel flow Q_K:

$$Q_K = \sum_{j=1}^{m} Q_K^j. \tag{57}$$

Then we can obtain this formula:

$$\widehat{\Omega}^{OR\,FeO} = Q_{OR} - \hat{Q}_{OR} = k \cdot (\{FeO_{MIX} - FeO_{SNT}\} \cdot Q_{MIX} - \\ -\{FeO_{MIX} - FeO^*_{SNT}\} \cdot Q^*_{MIX}) = \\ = k \cdot (FeO_{MIX} \cdot Q_K - FeO_{MIX} \cdot \sum_{j=1}^{m} Q_K^j + \\ +FeO^*_{SNT} \cdot \sum_{j=1}^{m} Q_K^j - FeO_{SNT} \cdot Q_K + \\ +\sum_{j=1}^{N-1} Q^j \cdot (FeO^*_{SNT} - FeO_{SNT})) = k \cdot (Q_K \cdot (FeO_{MIX} - \\ -FeO_{SNT}) + \sum_{j=1}^{m} Q_K^j \cdot (FeO^*_{SNT} - \\ -FeO_{MIX}) + \sum_{j=1}^{N-1} Q^j \cdot (FeO^*_{SNT} - FeO_{SNT})). \tag{58}$$

Dividing both sides by k coefficient we will get:

$$\Omega^{OR\,FeO} = (Q_K \cdot (FeO_{MIX} - FeO_{SNT}) + \\ +\sum_{j=1}^{m} Q_K^j \cdot (FeO^*_{SNT} - FeO_{MIX}) + \\ +\sum_{j=1}^{N-1} Q^j \cdot (FeO^*_{SNT} - FeO_{SNT})). \tag{59}$$

As a result of all these calculations we have obtained a system of equations with m unknowns. It can be seen that this system does not have a solution because the number of unknowns $m < n$:

$$\begin{cases} (M_K^\Sigma - M_K^*) = \Omega^M \\ (W_K^\Sigma - W_K^*) = \Omega^W \\ (S_K^\Sigma - S_K^*) = \Omega^S \\ (V_K^\Sigma - V_K^*) = \Omega^V \\ (A_K^\Sigma - A_K^*) = \Omega^A \\ (D_K^\Sigma - D_K^*) = \Omega^D \\ (FeO_K^\Sigma - FeO_K^*) = \Omega^{FeO} \\ (Q_{OR} - \hat{Q}_{OR}) / k = \Omega^{OR\,FeO} \\ (Q_C - \hat{Q}_C) = \Omega^{QC} \\ (Q_A - \hat{Q}_A) = \Omega^{AIR} \\ ((FeO)^{SNT} - (FeO)^{SNT\,\wedge}) = \Omega^{FeO\,SNT} \\ (CO - CO^\wedge) = \Omega^{CO} \\ (CO_2 - CO_2^\wedge) = \Omega^{CO_2} \end{cases}. \tag{60}$$

This system should be solved taking into account the following constraints:

$$0 \le Q_j^K \le Q^K, \\ \sum_{j=1}^{m} Q_j^K = Q^K. \tag{61}$$

Now we are ready to write the resultant function as a squared sum of the differences Ω^j divided by the variances $\sigma^2_{\Omega^j}$:

$$y = f(\Omega^j) = \sum_{j=1}^{P} \frac{(\Omega^j)^2}{\sigma^2_{\Omega^j}} \to \min. \tag{62}$$

This optimization problem can be considered as a nonlinear programming problem. The minimizing function is not convex, so in order to find the global minimum of it we used particle swarm optimization technique which is described in [13-14].

The solution to this problem will be the consumptions Q_j^K of all types of the solid-fuel flow.

Comparing the results Q_j^K with the expected values of the consumptions $\hat{Q}_j^K$ we can get:

$$Q_j^K - \hat{Q}_j^K = \delta_j. \tag{63}$$

These errors (63) form a vector $\Phi = (\delta_1, ..., \delta_m)$.

Based on the vector Φ we can make a decision about the necessity of correction of the solid-fuel flow consumption.

The expressions for $\Omega^S, \Omega^V, \Omega^A, \Omega^W$ were included as the system equations and not as constraints because the information about the solid-fuel flow composition is not precise.

Finally, the minimizing function can be written as follows:

$$\begin{aligned} y = f(\Omega^j) = \sum_{j=1}^{P} \frac{(\Omega^j)^2}{\sigma^2_{\Omega^j}} &= (\Omega^{FeO})^2 / \sigma^2_{\Omega^{FeO}} + (\Omega^A)^2 / \sigma^2_{\Omega^A} + \\ &+ (\Omega^V)^2 / \sigma^2_{\Omega^V} + (\Omega^S)^2 / \sigma^2_{\Omega^S} + (\Omega^W)^2 / \sigma^2_{\Omega^W} + \\ &+ (\Omega^M)^2 / \sigma^2_{\Omega^M} + (\Omega^{OR\,FeO})^2 / \sigma^2_{\Omega^{OR\,FeO}} + (\Omega^{QC})^2 / \sigma^2_{\Omega^{QC}} + \\ &+ (\Omega^{AIR})^2 / \sigma^2_{\Omega^{AIR}} + (\Omega^{FeO\,SNT})^2 / \sigma^2_{\Omega^{FeO\,SNT}} + (\Omega^{CO})^2 / \sigma^2_{\Omega^{CO}} \\ &+ (\Omega^{CO_2})^2 / \sigma^2_{\Omega^{CO_2}} + (\Omega^D)^2 / \sigma^2_{\Omega^D} \to \min. \end{aligned} \tag{64}$$

In the fig. 2, we presented the results of the proposed algorithm for the experimental data from MMC.

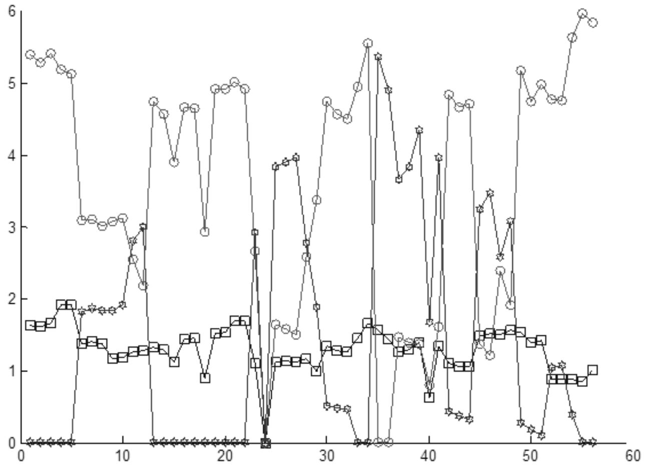


Fig. 2 Reconstruction of the solid-fuel flow composition (circle – coke breeze 0-10; diamond – coke breeze 0-25; square – sludge)

IV. OPTIMAL CONTROL OF THE SINTERING PROCESS BASED ON THE INFORMATION ABOUT THE SOLID-FUEL FLOW COMPOSITION

In this section we will briefly describe how to correct the solid-fuel flow consumption according to the vector $\Phi = (\delta_1, ..., \delta_m)$.

The difference δ_j can be represented as follows:

$$\delta_j = (Q_j^S - Q_j^R), \tag{65}$$

where Q_j^S is the expected value of consumption of a j type of the solid-fuel and Q_j^R is the current value of the consumption of a j type of the solid-fuel.

Then, based on the heat of combustion T_j of a j type of the solid fuel, we can represent the overall heat of combustion of the solid-fuel flow as follows:

$$\begin{aligned} T_\Sigma^S &= \sum_{j=1}^{n} Q_j^S T_j, \\ T_\Sigma^R &= \sum_{j=1}^{n} Q_j^R T_j. \end{aligned} \tag{66}$$

Now we can write the heat balance equation for our case:

$$T_\Sigma^S - T_\Sigma^R = 0. \tag{67}$$

If we expand the previous expression we will get:

$$\sum_{j=1}^{n} Q_j^S T_j - \sum_{j=1}^{n} Q_j^R T_j = 0 \tag{68}$$

From the previous expression, we can find the consumption of the solid-fuel flow, if we write the expression for the set point consumption as follows:

$$Q_j^S = Q_\Sigma D_j^S T_j, \tag{69}$$

where D_j^S is the portion of some j solid-fuel type in the solid-fuel flow.

Therefore we can rewrite the expression (68) in the following way:

$$Q_\Sigma^\chi D_j^S T_j + \sum_{j=2}^{n} Q_j^S T_j - \sum_{j=1}^{n} Q_j^R T_j = 0. \tag{70}$$

After some simple modifications, we can get:

$$Q_\Sigma^\chi = \frac{\sum_{j=1}^{n} Q_j^R T_j - \sum_{j=2}^{n} Q_j^S T_j}{D_j^S T_j}. \tag{71}$$

Then we can write the following equation:

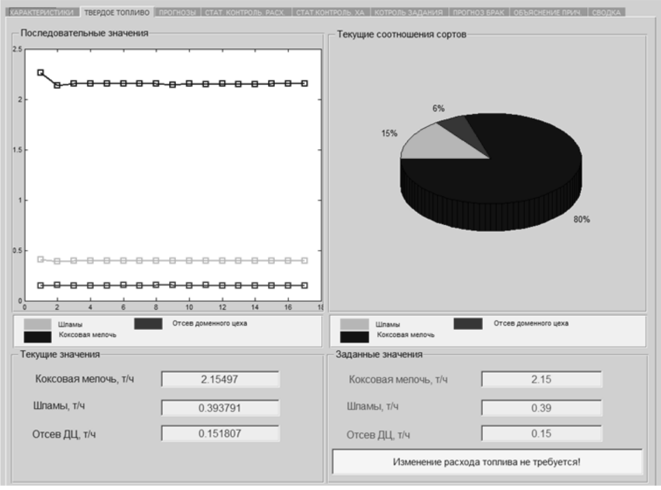
$$\Delta Q_\Sigma = Q_\Sigma - Q_\Sigma^\chi. \tag{72}$$

From the previous equation, we can finally find the solid-fuel flow consumption:

$$Q_\Sigma = Q_\Sigma + \Delta Q_\Sigma. \tag{73}$$

Now the consumption of the solid-fuel flow can be corrected according to the calorific properties of the solid-fuel types comprising the solid-fuel flow.

An example of the graphical user interface of our expert system is shown in the fig. 3. It can be seen that our system preserves history and displays the current solid-fuel flow composition as the 3D pie chart. The recommendations about corrections are displayed at the bottom right corner of the form.



Коксовая мелочь, т/ч 2.15497
Шламы, т/ч 0.393791
Отсев ДЦ, т/ч 0.151807

Коксовая мелочь, т/ч 2.15
Шламы, т/ч 0.39
Отсев ДЦ, т/ч 0.15

Изменение расхода топлива не требуется!

Fig. 3 Main tab of our expert system

V. CONCLUSION

For the last decade, many intelligent systems were proposed to control the iron ore sintering process. However, these works take into account only available information, which can be directly measured or obtained using known equations, which describe the process. The solid-fuel flow usually consists of several different types of fuels. The information about the solid-fuel flow composition is often unavailable. This can lead to decreasing quality of the sinter. In order to cope with this problem, in this article, we proposed the expert system which takes real-time data from the sintering process and reconstruct the solid-fuel flow composition by means of the indirect measures. In order to do so, we developed the optimization model, which uses different parameters such as: chemical composition of the sintering gas, chemical composition of the mix material, chemical composition of the solid-fuel flow, etc.

Reconstructed composition of the solid-fuel flow can be used to take corrective actions in order to stabilize quality of the sinter. The algorithm for correction of the solid-fuel flow consumption was proposed. Further extension of this system will be development based on the extensive use of the time series which characterize the sintering process. We have already done some research work in that direction [15-17]. We think that wavelet based data mining methods can be successfully used in order to detect different faults like equipment faults or faults of the sintering plant personnel.

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