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The analysis of the effect of iron-ore raw material composition on blast-furnace smelting parameters by the mathematical model method

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Abstract. The paper considers capabilities of the developed model-based decision support system (URFU-MMK model of the blast-furnace process) for diagnostics of operation and prediction of production situations at blast furnaces. It presents some results of practical application of the developed system and it also gives recommendations for certain aspects of process task solving on the basis of the model-based decision support system. It presents calculation results of blast furnace operation with a high portion of non-fluxed pellets from Sokolovsk-Sarbay Ore Mining and Processing Group in burden of MMK's blast furnaces with different content of local sinter. It shows that with a higher portion of non-fluxed pellets (up to 60%) in the charged burden it is necessary to charge limestone in the furnace to achieve the required basicity of blast-furnace slag. In order to reduce the amount of crude limestone to be charged, it is necessary to produce sinter of high basicity. As far as the portion of pellets in the charged burden increases, concentration of magnesia in blast-furnace slag decreases. To increase concentration of magnesium oxides in slag, it is efficient to use combined basic flux consisting of 70% normal limestone and 30% dolomite limestone.

1. Introduction
Due to a great energy intensity and complexity of blast-furnace production, the role of scientifically proven solutions aimed at solving a complex of process tasks relating to definition of the optimum composition of blast-furnace and sinter burdens, selection of efficient slag, blast, gas dynamic and heat conditions of blast-furnace smelting is getting more and more important [1–10].

2. Model for selecting a composition of iron-ore raw materials and fluxes
The generalized structure of the model for selecting a composition of iron-ore raw materials and fluxes is given in figure 1. The analysis of input and output parameters makes it possible to state that the mathematical model shall include the following interrelated calculation blocks: sinter composition, heat conditions, slag conditions, gas dynamic conditions.

The model is divided into two parts, i.e. basic state model and predictive model. The basic (reference) state model allows assessment of the process state by averaged parameters during the base (reference) period of blast furnace operation. In this case, the actually available information on blast furnace operation is used. The predictive model allows assessing parameters of the blast-furnace process on the basis of the results obtained with the use of the base state model in case of changes in smelting conditions. The works [11-21] describe in detail the main design ratios and example implementation of this model.

Modelling of final slag properties includes the following blocks:

- definition of final slag output, composition and viscosity polytherm (slag viscosity dependence on slag temperature);
- calculation of sulphur-carrying power of slag and sulphur content in iron;
- diagnostics of slag conditions.

The calculation of *the slag output and composition* is based on the material balance equation for main chemical elements and entities. The slag output is calculated by the balance of slag-forming elements. The analytical *calculation of slag viscosity* is made by mathematical treatment of the threefold slag system diagram CaO–Al2O3–SiO2 at 1400 and 1500°C in the range of the real viscosity values of blast-furnace slags and use of known relationship between homogeneous melted slag viscosity and temperature. A provision is made for introduction of correction for content of other oxides (MgO, TiO_2) in slag, etc.

The parameters of the obtained viscosity polytherm are given below:

- slag viscosity at the given temperature: at the output – η_{sl}, 1400°C, 1450°C, 1500°C;
- slag viscosity gradients $\Delta\eta_{1400}^{1500}$ show slag stability in the range of final (operating) temperatures numerically equal to a change in slag viscosity in case of a change in the slag temperature by 1°C in the range from 1400°C to 1500°C, poise/°C.

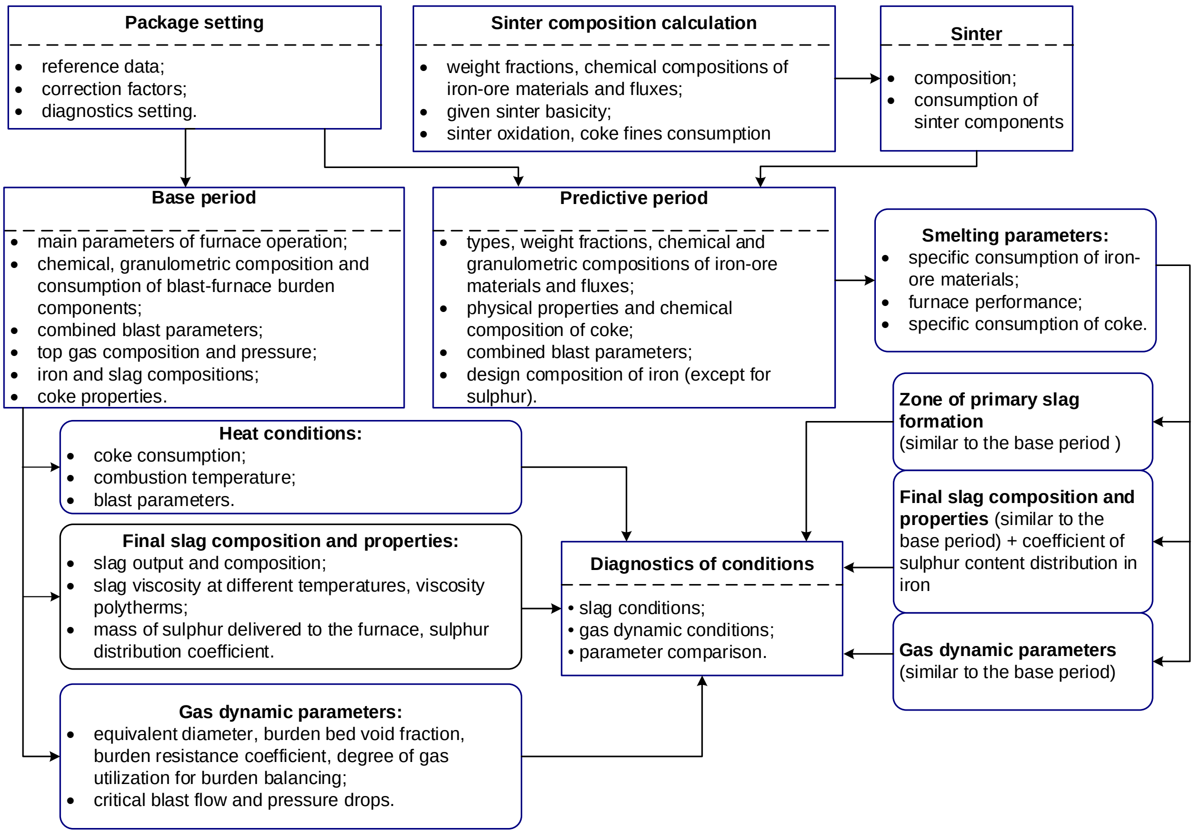

Figure 1. Structure of the model for selecting a composition of iron-ore raw materials and fluxes.

3. Model calculation variants

A provision is made for multivariance of predictive period modelling. The variants of problem solving are given below.

3.1. Project 1

Prediction of performance, coke consumption, consumption of iron-ore materials, properties of preliminary and final slag, gas dynamic parameters of smelting and thermal state is performed with given weight fractions and compositions of all iron-ore materials and fluxes charged in the furnace.

3.2. Project 2

Correction of blast furnace operation in case if changes in properties of iron-ore raw materials and fluxes is made by composition of one component of iron-ore part of blast-furnace burden, e.g. local sinter. Unlike the previous variant, this variant calculation is made with known compositions of all materials charged in the blast furnace, except for local sinter. Additionally, in a result of the calculation the required composition (consumption of iron-ore components, coke fines and fluxes) of sinter burden is determined.

In general, the rational conditions of blast-furnace smelting with changes in supplies of iron-raw raw materials for blast furnaces, iron-ore components of sinter burden as well as with changes in coke properties are provided by correcting:

- weight fractions and chemical composition of iron-ore components of sinter burden;
- flux consumption for sinter burden;
- flux consumption for blast-furnace burden;
- weight fractions and chemical composition of iron-ore components of blast-furnace burden;
- blast parameters and parameters of combined blast;
- any combination of the above options.

4. Process task solving

Below capabilities of process task solving are illustrated through the example of blast-furnace burden composition selection.

Due to the planned reconstruction of the sintering plant at Magnitogorsk Iron and Steel Works (MMK), the ratio of sinter and imported non-fluxed iron-ore pellets of Sokolovsk-Sarbay Ore Mining and Processing Group (SSGPO) in blast furnaces will change, the portion of pellets in burden can increase from 35 % (at present) to 60 %. With a bigger amount of non-fluxed pellets, a number of problems related to different chemical compositions of pellets and sinter as well as to different physical properties of these iron-ore materials will appear. With an increased consumption of non-fluxed pellets in burden, basicity of charged iron-ore materials decreases and charging of basic flux, i.e. limestone, into the furnace is necessary to get the required slag basicity.

To reduce the amount of crude limestone to be charged in the furnace, it is practical to be aimed at production of high-basicity sinter. The maximum basicity of sinter produced in MMK's sintering machines reached the value CaO/SiO_2 = 2.10. The tentative calculations show that sinter basicity (when the portion of pellets in burden is 60%) shall be CaO/SiO_2 = 2.7 to completely exclude charging of crude limestone into the furnace. Production of sinter with this basicity at MMK's sintering plant is problematic and, therefore, the basicity of produced sinter is taken CaO/SiO_2 = 2.10 for further calculations.

The next problem related to a larger amount of SSGPO's pellets in the iron-ore part of burden is a lower MgO concentration in final blast-furnace slag. This will lead to a larger slag viscosity and worse slag filtration through the coke packing as well as loss in sulphur-carrying power of slag and deterioration of iron quality because of larger sulphur content.

Due to a wider melting temperature range of pellets in comparison with sinter – by 30-50 °C (according to studies [6, 7]), an increase in the melting temperature range of the iron-ore mixture and increase in the lower gas pressure drop should be expected. Therefore, when making predictive calculations of blast-furnace smelting with a high portion of pellets in burden, a provision is made for addition in sinter burden of components increasing MgO content in sinter, i.e. dolomite limestone and Bakal siderite ore.

Calculations of blast-furnace burden with a high portion of pellets in the mixture with sinter for MMK's blast furnaces were made in the following sequence. In accordance with the data of sinter production, the averaged composition of sinter burden was determined. It shall be noted that at present the iron-ore part of sinter burden includes about 30 components. In one of the predictive calculation variants, Bakal siderite ore was added to the components of sinter burden. Normal limestone and limestone/dolomite limestone mixture were used as fluxing agents.

When calculating the composition of sinter with basicity CaO/SiO_2 = 2.10, we considered that sinter burden included blast-furnace dust (1.7%). As a solid fuel, coke fines are used and we were taking its consumption equal to 5.0% in all calculation variants. The calculation of sinter composition was made in accordance with the method of Prof. V.I. Korotich [8]. FeO content in sinter was taken 10.0 % for all calculation variants.

Out of many calculation variants, we have chosen four variants of the sinter composition calculation. In the *first* variant, normal limestone is used as a flux for sintering: in the *second* variant – a mixture of basic fluxes, i.e. 72.5 % of normal limestone and 27.5 % of dolomite limestone; in the *third* variant, sinter burden included Bakal siderite ore (10%); in the *fourth* variant, a combined flux (70% of normal limestone and 30 % of dolomite limestone) was used for MMK's sintering process. The purpose of calculating flux added for sintering is to obtain MgO concentration in final blast-furnace slag within 9-10 %. The chemical composition of sinter mixtures is given in table 1 in four variants. 1.

Table 1. Calculated compositions of MMK's sinter with basicity CaO/SiO_2 = 2.10 with addition in sinter burden of different fluxes and Bakal siderite ore

Type of produced sinter	Content of elements and oxides in sinter, mass % %											
	Fe	Mn	S	P	Fe_2O_3	FeO	CaO	SiO_2	Al_2O_3	MgO	TiO_2	MnO
Sinter-1 (flux – limestone)	53.47	0.21	0.01	0.02	65.27	10.00	13.88	6.61	1.86	2.01	0.27	0.27
Sinter-2 (flux – 72.5% limestone + 27.5% dolomite limestone)	53.06	0.21	0.01	0.02	64.69	10.00	13.64	6.49	1.83	2.97	0.27	0.27
Sinter-3 (addition of Bakal siderite ore 10.0% in sinter)	52.95	0.28	0.01	0.02	64.53	10.00	13.86	6.60	1.89	2.65	0.26	0.36
Sinter-4 (flux – 70% limestone + 30% dolomite limestone)	53.00	0.21	0.01	0.02	64.61	10.00	13.61	6.48	1.83	3.10	0.27	0.27

On the basis of these data we made calculations of blast-furnace burdens with determination of the total consumption of iron-ore materials (MMK's sinter and non-fluxed pellets), coke consumption and required consumption of crude limestone, softening start temperature and melting temperature of the iron-ore mixture, melting temperature range, slag composition and output as well as slag properties, i.e. viscosity at 1400, 1450 and 1500°C and viscosity gradient determining slag stability in the temperature range from 1400 to 1500°C [6].

The composition of blast-furnace burden was as follows: for calculation variants 1-3 – 40 % of MMK's sinter and 60 % of SSGPO's pellets and for calculation variant 4 – 40 % of MMK's sinter, 30 % of SSGPO's pellets and 30 % of Mikhailovsky GOK' pellets. All the calculations were made on condition that Si content in iron should be 0.70 % with final slag basicity CaO/SiO_2 = 1.05 for the following input data: blast temperature is 1178 °C; oxygen content in blast is 25.88 %; natural gas flow rate is 103 m^3/t of iron; ash content in coke is 13.08 %; sulphur content in coke is 0.50 %; coke strength M_{25} = 87.99 %. When solving the problem, we assumed that production technology and chemical composition of SSGPO's iron-ore pellets remain unchanged. The coke consumption was calculated by the method of Prof. A.N. Ramm [9].

5. Model calculation results

The calculation results are given in table 2.

Table 2. Some parameters of blast-furnace smelting variants in MMK's furnaces.

Parameter	Blast-furnace smelting variants			
	I[a] Sinter-1	II[a] Sinter-2	III[a] Sinter-3	IV[b] Sinter-4
Total consumption of iron-ore materials, kg/t of hot metal	1603.4	1607.8	1608.5	1604.0
Specific consumption, kg/t of hot metal:				
coke	443.8	445.6	445.1	449.4
crude limestone	31.8	32.4	28.4	56.4
slag	314	321	320	328
Slag composition, %:				
(CaO)	38.47	37.53	37.94	39.64
(SiO_2)	36.64	35.74	36.13	37.75
(Al_2O_3)	13.88	13.56	13.75	10.88
(MgO)	7.65	9.86	8.83	8.63
(TiO_2)	1.59	1.56	1.55	1.47
Slag viscosity, poise/(Pa·s) at temperature, °C:				
1400	17.3/(1.73)	16.7/(1.67)	17.0/(1.70)	13.9/(1.39)
1450	8.2/(0.82)	7.5/(0.75)	7.8/(0.78)	5.8/(0.58)
1500	4.7/(0.47)	4.2/(0.42)	4.4/(0.44)	3.2/(0.32)
Slag viscosity gradient, poise/°C	0.22	0.24	0.23	0.29
Viscoplastic characteristics of iron-ore mixture, °C:				
softening start temperature	1157	1167	1163	1162
melting temperature	1453	1444	1447	1436
melting temperature range	295	278	284	274

Note. Slag basicity CaO/SiO_2 = 1.05.
[a]Blast-furnace slag composition: 40% MMK's sinter with basicity CaO/SiO_2 = 2.1 + 60% SSGPO's pellets.
[b]Blast-furnace slag composition: 40% MMK's sinter +30% SSGPO's pellets + 30% Mikhailovsky GOK's pellets.

The calculations show that when charging the burden of Variant 1 into the furnace the composition of the resulting slag is extremely unfavorable - Al2O3 concentration = 13.88% and MgO = 7.65 % (refer to table 2). At the temperature of 1450°C slag has an unacceptably high viscosity – 8.2 poise (0.82 Pa·s) [6]. According to the previous studies of slag conditions of MMK's blast-furnace smelting, it was determined that an increase in slag viscosity η_{1450} > 6.5 poise (0.65 Pa·s) is accompanied by a degraded slag flow ability and reduced efficiency of hot metal desulphurization. A probability of an increased lower gas pressure drop and limited smelting rate also grows up.

In order to increase magnesia concentration in slag for the purpose of increasing slag sulphur-absorbing ability and improving temperature characteristics of iron-ore material melting, Calculation

Variant II was performed (refer to table 2): use of combined flux for sintering. Blast-furnace smelting of Sinter-2 together with SSGPO's pellets in the ratio of 40:60 % leads to an increased magnesia concentration in slag up to MgO = 9,86 % (refer to table 2) and improved viscoplastic characteristics of the iron-ore mixture charged in the blast furnace: Δt_{melt} decreases from 295°C (in Variant I) to 278 °C. Slag viscosity at 1450°C also decreases to η_{1450} = 7.5 poise (0.75 Pa·s). However, this parameter is also too high and does not conform to normal progress of blast-furnace smelting in slag conditions.

With the same ratio of sinter and SSPGO's pellets (40:60%) in blast-furnace burden, Calculation Varian III was performed to check if it is efficient to add Bakal siderite ore in MMK's sinter burden to obtain blast-furnace slags with in an increased MgO concentration. In fact, 10% addition of Bakal siderite ore leads to final slags with content of MgO = 8.83 %. However, characteristics of slag conditions are worse in efficiency than in Variant II – MgO content in slag is less (8.83 instead of 9.86) and Al_2O_3 concentration in slag is even slightly higher. The temperature characteristics of iron-ore material melting are worse – the melting range Δt_{melt} increases to 284 °C (in Variant II Δt_{melt}=278 °C). In Variant III slag viscosity at 1450 °C is not acceptable – η_{1450} = 7.8 poise (0.78 Pa·s). Thus, addition of Bakal siderite ore into MMK's sinter burden does not solve the problem of decreasing in slag of Al_2O_3 = 13.75%.

To get the required values of Al_2O_3 and MgO concentration in slag, Calculation Variant IV was performed: with burden consisting of 40% sinter and different pellets (30% SSGPO's pellets and 30% Mikhailovsky GOK's pellets). The calculations show that in this variant the characteristics of slag viscosity in the operating temperature range conform to the required characteristics at the temperature of 1450°C – η_{1450} = 5.8 poise (0.58 Pa·s) and at the temperature of 1500 °C – 3.2 poise (0.32 Pa·s). The melting temperature range determining the viscoplastic zone thickness is minimum for all the above variants – Δt_{melt} = 274°C. However, in order to get the assigned slag basicity CaO/SiO_2 = 1.05 with the chosen ratio of iron-ore materials, it is required to charge crude limestone in the quantity of 56.4 kg/t of hot metal and in a result the specific coke consumption is somewhat higher – 449.4 kg/t of hot metal.

6. Conclusions

1. We developed a model-based decision support system which allows diagnostics of blast-furnace operation on the basis of actual and design data as well as solving a set of process task in the predictive mode.
2. With a higher portion of non-fluxed pellets (up to 60%) in the charged burden, it is necessary to charge limestone in the furnace to achieve the required basicity of blast-furnace slag.
3. In order to reduce the amount of crude limestone to be charged in the furnace, high-basicity sinter is required. MMK's sintering plant uses sinter with basicity CaO/SiO_2 = 2.1 for the sintering process and this value is accepted as the maximum value for predictive calculations.
4. As far as the portion of SSPGO's pellets in the charged burden increases, MgO concentration in blast-furnace slag decreases. To increase MgO concentration in slag, it is efficient to use combined basic flux consisting of 70% normal limestone and 30% dolomite limestone for sinter production.
5. The calculation analysis shows that a higher MgO concentration in blast-furnace slag achieved by addition of Bakal siderite ore into sinter burden is less preferable as compared to use of a mixture of normal and dolomite limestone for sinter production.
6. Additional calculations show that Al_2O_3 content in slag grows up when the portion of SSGPO's pellets in burden is increased. To reduce its content to the level acceptable for normal slag conditions (Al_2O_3 ≈ 10–12%), it is efficient to replace partially SSGPO's pellets with Mikhailovsky GOK's pellets. It is established by calculations that Al_2O_3 concentration in blast-furnace slag reaches ≈10.9 % when blast-furnace burden consists of 40 % MMK's sinter with basicity CaO/SiO_2 = 2.1, 30 % SSGPO's pellets and 30% Mikhailovsky GOK's pellets.

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