Comprehensive index of compound blast furnace smelting

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An actual direction in the development of blast-furnace smelting technology is the implementation of stable operating modes of blast furnaces in terms of the parameters of the used charge materials and hot combined blast. For this purpose, complex indicators characterizing the thermal and reduction modes of blast furnace smelting, and integral indicators of iron ore raw materials (IORM) quality are being studied. The object of the study is the blast furnace process under the conditions of PJSC NLMK. The database of the main indicators of the operation of blast furnaces No. 4, 6 and 7 for the period 2013–2018 was analyzed. The furnaces operate under raw material conditions, with similar combined blast parameters and coke consumption. When the consumption of natural gas, pulverized coal and process oxygen changes, the values of the degree of compensation (the ratio of the consumption of reducing additives to the consumption of process oxygen) are in the range of 0.9–1.1. This provides a constant level of hearth heating, stability of the gas-dynamic mode of melting and coke consumption. At the same time, the different level of development of the processes of indirect (Ri) and direct (rd) reduction in blast furnaces No. 4, 6 and 7 makes it possible to perform correct studies of the features of blast furnace smelting in a wide range of Ri and rd values.
It has been established that under the conditions of stable operation of blast furnaces on raw materials from sinter and pellets using combined blast, the type of dependence of the sulfur and silicon content in pig iron on the values of the integrated iron ore raw materials quality index is determined by degree development level of direct reduction processes rd. It has been established that the mode of blast furnace smelting with natural gas, pulverized coal and process oxygen, characterized by the level of rd values less than 20–25 %, is distinguished by the presence of a pronounced extreme dependence of coke consumption and productivity on the parameters of the combined blast.
Key words: blast furnace smelting, iron ore raw materials, combined blast, pulverized coal fuel, integral indicator, degree development level of direct reduction processes, chemical composition of pig iron.
DOI: 10.17580/cisisr.2022.01.02

Relevance

According to experts, the defining directions for the development of blast furnace production technology in the last decade are: the use of alternative types of blast components to reduce the «carbon footprint»; increase in consumption of high-quality iron ore raw materials (IORM); wide use of information technologies («digital twins», collection of «big data», virtual and augmented reality). It can be stated that technologists are striving to implement stable operating modes of blast furnaces in terms of the parameters of the charge materials used and the combined hot blast. It can be stated that technologists are striving to implement stable operating modes of blast furnaces by parameters of used charge materials and the combined hot blast. For this purpose, complex indicators characterizing the thermal and reduction modes of blast-furnace smelting, integral indicators of iron ore quality, linking the metallurgical characteristics of iron ore with the parameters of reduction, mass and heat transfer processes, and the chemical composition of iron [1-5] are investigated.

Goal of the work

Search and study of the dependence of the main technical and economic indicators of blast furnace smelting (coke consumption and productivity) on the parameters of the combined blast and complex indicators (R_i and r_d) characterizing the reduction and thermal regimes of the blast furnace process.

Search for the dependence of the composition of pig iron (contents of silicon and sulfur) on the quality of iron ore (an integral indicator of iron ore quality) and complex indicators (R_i and r_d).

Object of study

The database of average daily performance indicators of blast furnaces No. 4, 6 and 7 of PJSC NLMK for the period from January 1, 2013 to December 31, 2018, analyzed in detail in publications [4-9], was studied. Useful volume of BF No. 4 is 2,000 m^3, hearth diameter is 10.0 m, useful volume of BF N6 is 3,200 m^3, hearth diameter is 12,0 m, effective volume of BF No. 7 is 4,291 m^3, hearth diameter is 13.1 m.

The operating mode of NLMK's blast furnaces in the analyzed period was characterized by stability (**Table 1**). BF No. 4 operated only on coke produced by NLMK, BF No. 6 and BF No. 7 also used imported coke from the Altai Koks Plant. The share of sinter in the iron ore part of the furnace charge was 60–70 %, the share of blast furnace lump ore did not exceed 1.0 %. In the period 2013–2016 the furnace charge was dominated by pellets from Lebedinsky GOK and Mikhailovsky GOK. In November 2016, after the commissioning of a new plant at Stoilensky GOK with a design capacity of 6 million tons of pellets per year, NLMK began a phased transition to the use of Stoilensky GOK pellets in the furnace charge. In January 2017, LGOK and MGOK pellets were replaced by SGOK pellets with a stable share of 90 % to 100 % in the pellet mix. The share of pellets from the Kachkanar GOK during the entire period under study did not exceed 7 % of the weight of the iron ore part of the charge.

The blast furnaces were powered by oxygen enriched blast using natural gas (NG) and pulverized coal fuel (PCF). The combined use of PCF and natural gas at BF No. 4 started in April 2014, at BF No. 6 and BF No. 7 in May 2017.

During the review period, the slag regime of blast furnaces was stable.

Methodology

For each daily operation period of blast furnaces, the total material balance of the smelting, the balances of the main basic elements (iron, oxygen, carbon, hydrogen, nitrogen, sulfur, phosphorus) and slag-forming components (CaO, MgO, SiO_2, Al_2O_3) are compiled. The convergence of the balance for each mentioned position was to be within 0.5 % (abs.). Subject to this condition, the heat balance of the process was calculated according to the methodology of A. N. Ramm [10]. The condition for the correctness of blast furnace smelting indicators was the value of heat losses (determined by the difference between the incoming and outgoing parts of the balance) in the range of 4–6% rel. The calculation of the development of direct reduction processes (rd) indicator was carried out according the M. A. Pavlov's method.

The integral indicator of iron ore quality was determined using the Harrington method [11-13] as a function of the chemical composition and strength index in the recovery process:

$K_{sh} = f(Fe_{tot}/SiO_2), CaO/SiO_2, Al_2O_3/SiO_2, MgO/SiO_2, R_2O/CaO, X_{+5}),$

where Fe_{tot}, SiO_2, CaO, Al_2O_3, MgO_2 – component content in iron ore, mass fraction, %;

R_2O – total oxides content K_2O and Na_2O), mass fraction, %;

X_{+5} - yield of usable material in accordance with test by GOST 19575–84

The visual analytics software Tableau was used to graphically represent the data and identify functional dependencies. Regression curves are obtained by approximating experimental data with a quadratic function. The values of the approximation reliability coefficients R_2 for the given analytical dependencies are in the range from 0.25 to 0.40 (except when they are shown directly on the graphs).

Research and results

The entire period under study is characterized by a slight increase (from 0.9 to 1.1) in the degree of compensation (the ratio of additional costs of pulverized coal and/or natural gas and process oxygen) with an increase in the parameters of the combined blast (consumptions of natural gas, pulverized coal and process oxygen). Operation in such an interval of the degree of compensation provides a stable level of values of the theoretical combustion temperature and the amount of reducing components of the hearth gas ($C_tO_d + C_dO_d + H_2$) [14-17]. In turn, as it is known from generally recognized literary sources [10, 14–24], the mentioned conditions of the blast-furnace process provide: a constant level of hearth heating and stability of the gas-dynamic mode of melting. At the same time, the different development processes level of direct (r_d) and indirect reduction (R_i) characterizes the different composition of hearth gases.

The presence of blast furnaces operating on a charge of similar composition and quality, with a stable thermal and gas dynamic mode, but with different parameters (development levels) of direct and indirect reduction processes makes it possible to perform correct studies of the features of the blast furnace process in a wide range of R_i values (from 66 to 92 %) and r_d (from 5 to 45 %).

The correctness of the performed calculations is confirmed by the well-studied and scientifically substantiated dependences obtained for the selected objects and the research period [10, 14–17]. This applies in particular to the following dependencies:

Table 1. **Some parameters of blast furnace smelting for the period 2013–2018 (average values or characteristic intervals of indicator values are given)**

Blast furnace	BF No. 4	BF No. 6	BF No. 7
Sinter / Pellets, % in the iron ore portion of the charge	67/33	65/35	65/35
Productivity using NG, t/m² × day	74.8	71.4	84.3
Productivity using NG + PCF, t/m² × day	70.3	70.7	83.6
Coke consumption using NG, kg/t of pig iron	382	400	405
NG consumption, m³/y of pig iron	129	122	120
Coke consumption using NG + PCF, kg/t of pig iron	315	325	331
PCF consumption, kg/t of pig iron	132	134	127
NG consumption, m³/y of pig iron	54	63	56
Oxygen content in the blast using NG, %	29.9	29.3	29.3
Oxygen content in the blast using NG + PCF, %	28.1	29.1	29.7
The degree of use of gases using PG, η, %	40-44	43-47	42-46
The degree of use of gases using PG + PCF, η, %	48-50	50-53	50-53
Degree development level of direct reduction processes, r_d,%	5–15	20–30	35–45
The moisture content in the blast, g/m³	1.02–18.70		
Silicon content in pig iron, % wt.	0.34–0.52		
Sulfur content in pig iron, % wt.	0.010–0.035		
Theoretical combustion temperature,°C	2050–2250		
Top gas temperature, °C	150–190		
Integral indicator of iron ore quality (K_{sh}), unit	0.53–0.59		

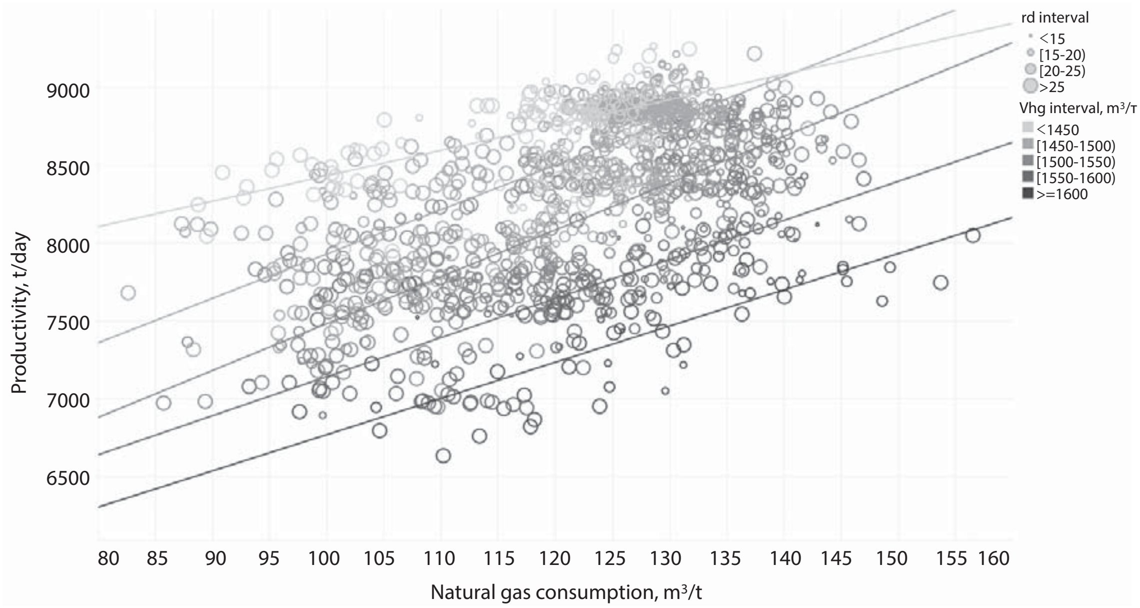

Fig. 1. Dependence of productivity on natural gas consumption, r_d and amount (output) of tuyere gas, blast furnace No. 6.

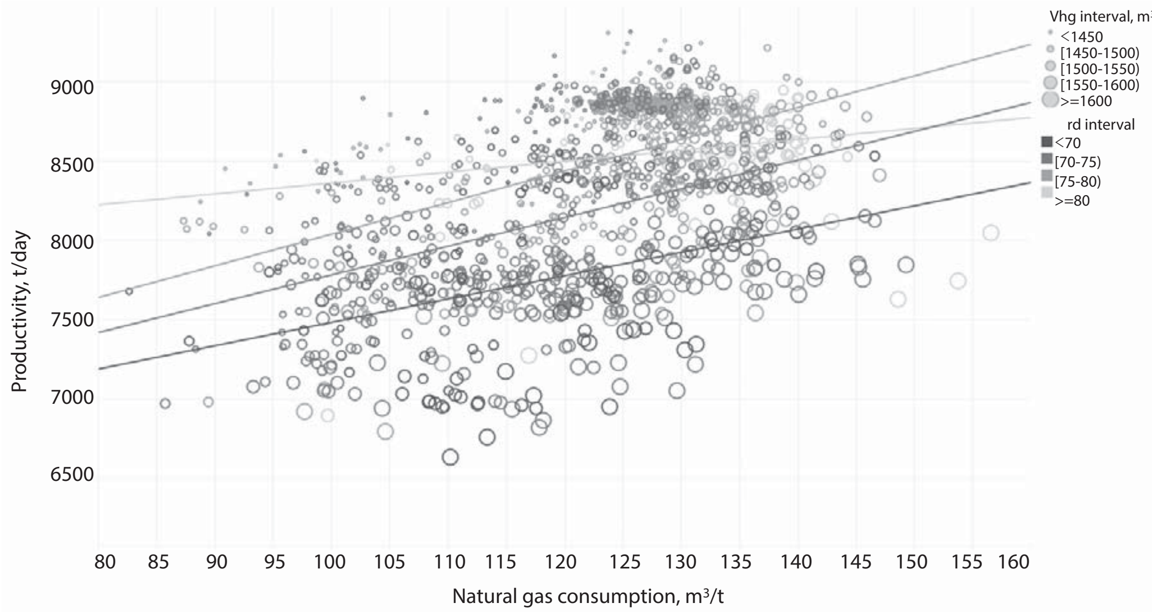

Fig. 2. Dependence of productivity on natural gas consumption, R_i and amount (output) of tuyere gas, blast furnace No 6.

• Performance from the output of tuyere (V_{tg}) and hearth (V_{hg}) gas;

• The use degree of the reducing ability of gases (ηCO, ηH_2, $\eta\Sigma$) from the output of the tuyere (V_{tg}) and hearth (V_{hg}) gas;

• The amount of reducing components of tuyere $(C_tO_d + H_2)_{tg}$ and hearth gas $(C_tO_d + C_dO_d + H_2)_{hg}$ from process oxygen consumption.

The graph in **Fig. 1** illustrates the impact of the development of reduction processes on productivity growth. When more increase in the consumption of natural gas contributes to the reduction in the consumption of coke, those more significantly the yield of hearth gases decreases (at the same consumption of NG) and the productivity increases. For example, at NG consumption of 120 m³/t of pig iron, decrease in tuyere gas yield for every 50 m³ (about 12 kg of coke) leads to an increase in productivity by about 5 %.

Joint consideration of the graphs in Fig. 1 and **Fig. 2** demonstrates the well known dependence from generally recognized theoretical works [10, 14–20]. At constant consumption of natural gas in the range of 100–140 m³/t of pig iron and a degree of compensation (NG/O_2 or $(NG+PCF)/O_2$) about 1.0, an increase in R_i by 1 % corresponds to a decrease in coke consumption by 1 % (about 4 kg /t of pig iron) and an increase in productivity by 1.5 %.

In the period of 1970–1990, the issue of the rd parameter as a complex indicator characterizing the thermal and

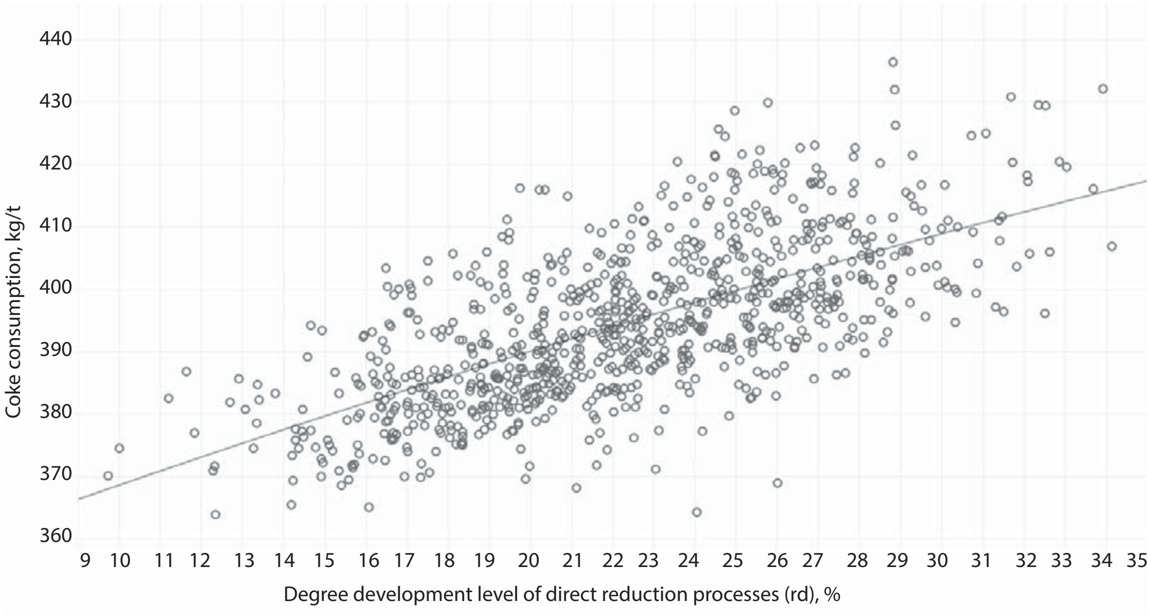

Fig. 3. Dependence of coke consumption on degree development level of direct reduction processes r_d (blast furnace No. 6).

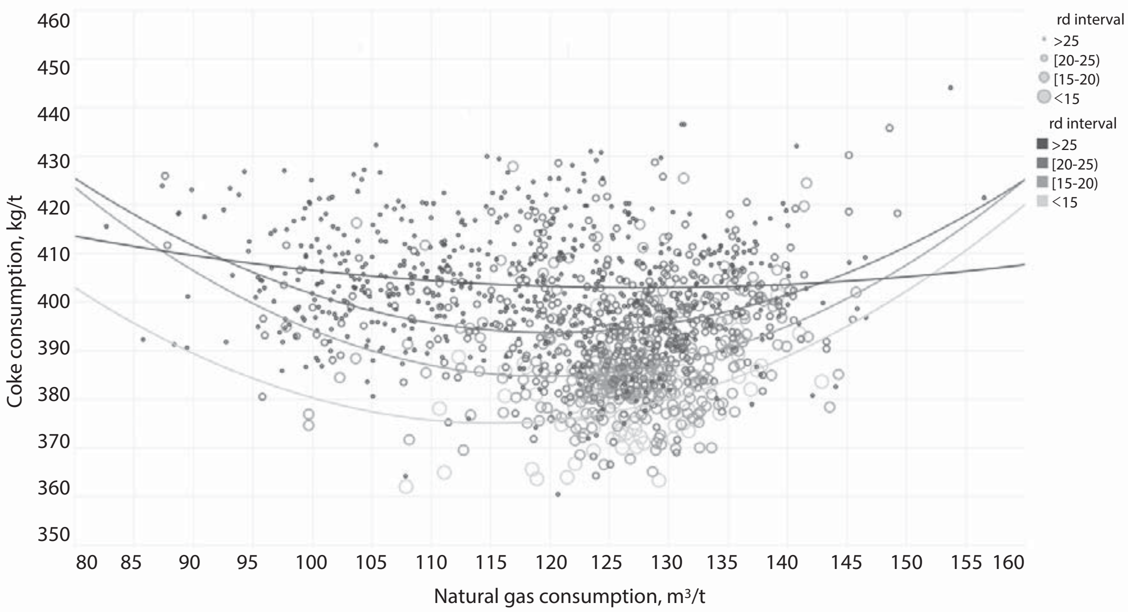

Fig. 4. Dependence of coke consumption on natural gas consumption, (blast furnace No. 6).

reduction modes of blast furnace smelting was studied in detail in the special national literature. It was noted that «the value of rd depends on many factors, including: the reducibility of iron ore components of the charge, the reactivity of coke, the intensity of blast-furnace smelting, the materials distribution, the state of the furnace profile, coke consumption, the flow rate and composition of injected fuel, blast composition, etc.» [14].

The general opinion of many authors [10, 14–24], who have been studying the blast furnace process on a multicomponent combined blast for a long time, can be characterized by the following quote: «In modern hot combined blast smelting and high quality iron ore charge, the need of coke is so low that a shortage of a reducing agent has become a widespread thing, and the development of a more economical direct reduction process in terms of reducing agent consumption has become inevitable. At the same time, the task of the technologist remained the same «to reduce as much as possible» the rd, only earlier he sought to reduce rd to zero, and the modern technologist – only to r_{dmin} ...» [17].

The results of the performed studies confirm the statements formulated above, which is illustrated, in particular, by the graph in **Fig. 3**.

At the same time, in previous studies [25-29] it was shown and theoretically substantiated that the operation of blast

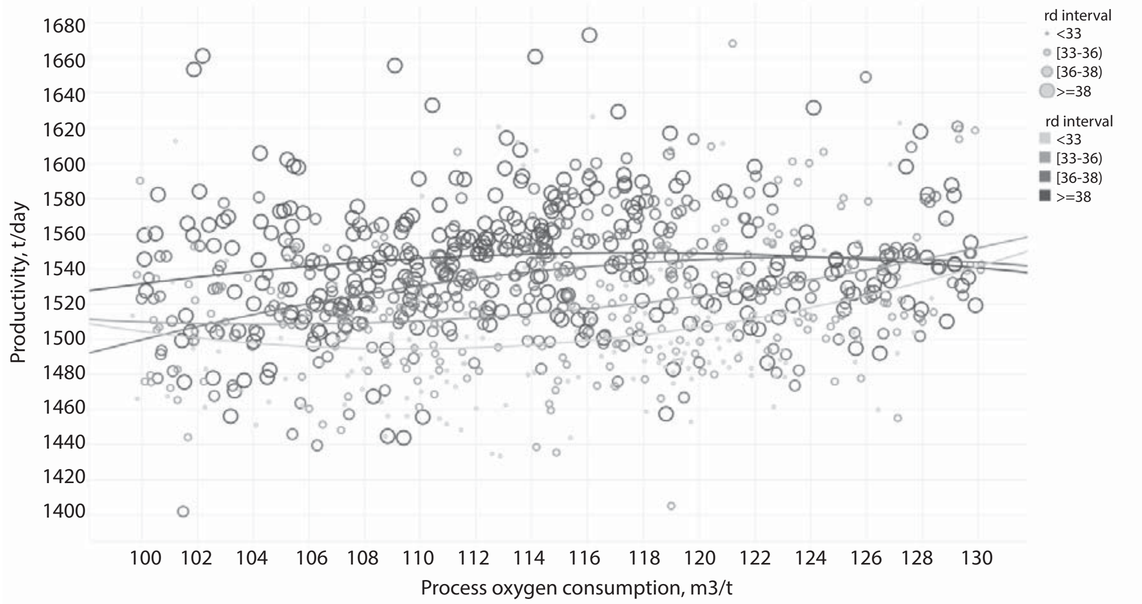

Fig. 5. Dependence of productivity on consumption of process oxygen, (blast furnace No. 7).

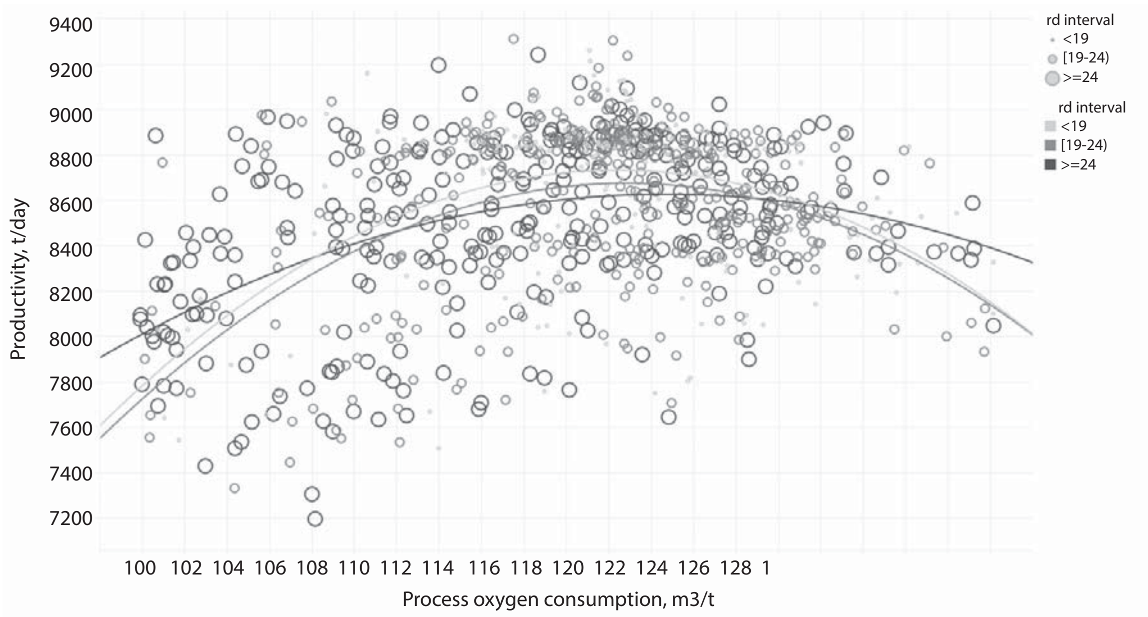

Fig. 6. Dependence of productivity on consumption of process oxygen, (blast furnace No. 6).

furnaces with combined blast parameters at a low level of the indicator is an unstable mode. Deviations from the optimal values of NG and O_2 consumption lead to an increase in coke consumption and a decrease in productivity. This is reflected in the form of dependencies of coke consumption (with a minimum for rd less than 25 %) and productivity on the consumption of natural gas and process oxygen (with a maximum for rd less than 25 %), examples of it are shown in **Fig. 4–6**.

The unstable mode of blast furnace smelting, characterized by r_d values less than 25 % is also indicated by the dependence of the sulfur and silicon content in pig iron on the values of the integrated iron ore quality index, which is illustrated by the data in **Table 2** [5].

Conclusions

1. Using a large array of industrial data, the reduction processes of blast furnace smelting on a combined blast of high parameters are studied. It is shown that the melting modes, characterized by value level of degree development of direct reduction processes (rd) less than 20–25 %, differ significantly from the melting mode with higher values of r_d.

2. It is confirmed that the mode of blast furnace smel-ting using natural gas, pulverized coal and process oxygen, characterized by r_d values level less than 20–25 %, is distinguished by the presence of a pronounced extreme dependence of coke consumption (with intervals of minimum values) and

Table 2. **Dependence type matching of coke consumption and productivity of blast furnace on the parameters of combined blast* (NG and O_2) and the composition of pig iron ([Si], [S]) on the integral indicator of iron ore** at different levels of degree development level of direct reduction processes, r_d.**

r_d, %	Coke consumption	Productivity	[Si]	[S]
30–42 (BF No. 7)	Decreasing	Increasing	Decreasing	Decreasing
12–30 (BF No. 6)	Extremum with minimum	Extremum with maximum	Increasing	Changes insignificantly

* NG and process oxygen consumption increases from 100 to 140 m^3/t of pig iron

** Integral indicator of iron ore quality (Кш) increase from 0.53 to 0.59 unit

productivity (with intervals of maximum values) from the parameters of combined blast (consumption of process oxygen, natural gas and pulverized coal).

3. It has been established that the type of dependence content of sulfur and silicon in pig iron on values of integral indicator of iron ore quality is determined by degree development level of direct reduction processes (r_d).

The studied and established relationships can be used in logical quantitative expert systems for predicting blast furnace process parameters.

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