The influence of parameters of slag conditions on blast furnace smelting performance and cast iron quality

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The analysis of production data on the operation of the blast furnace No. 2 for the period from 2021 to 2023 is carried out. The results of the influence of parameters of slag conditions on the technical and economic indicators (TEI) of blast furnace operation and the quality of cast iron are presented. It was found that when analyzing the performance indicators of the blast furnace operation and the results of desulfurization under conditions of instability of the composition of charge and slag, it is necessary to use the indicator of the total or complete slag basicity, which gives more objective results, unlike simple basicity. It is shown that the slag procedure should be characterized by a minimal basicity that ensures achievement of a specified cast iron quality, in order to achieve the best TEI of the blast furnace. To improve the conditions and results of metal desulfurization, it is advisable to adjust the slag composition towards increasing the MgO content to 9–10 % while reducing the level of simple slag basicity to 0.95 units and maintaining the value of the total basicity at the level of 1.16–1.18 units. In addition, it is expedient to ensure that the Al_2O_3/SiO_2 ratio is maintained at the level of 0.2–0.25 units. When maintaining the proposed slag conditions, in addition to improving the conditions and results of desulfurization, a decrease in slag amount can be expected. This, together with the improvement of the slag physical properties (viscosity and fluidity), will reduce coke consumption and provide conditions for increasing the blast furnace productivity.
Key words: blast furnace smelting, productivity, coke consumption, hot metal desulfurization, sulfur distribution coefficient, parameters of slag conditions, slag basicity.
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Introduction

Despite active development of alternative technologies of steel production, more than 90 % of steel products is manufactured at present time via the classical route, using blast furnace practice. The stable positions of blast furnace technology in the structure of steel production are caused by well-known advantages of blast furnace melting, such as high degree of used heat and chemical energy as well as efficiency of metal desulfurization [1–3]. At the same time, blast furnace stage, including coke making and ore preparation for melting, is the main consumer of energy resources and the main source of emission of contaminants in the iron and steel industry [4–6].

In this connection, integrated metallurgical works worldwide pay the most attention to the problems of energy saving and decrease of emission of greenhouse gases, what is especially actual taking into account the global trend for "carbon footprint" lowering [6–9].

Decrease of coke consumption is considered as one of the main directions for achieving energy efficiency and carbon capacity of blast furnace melting as well as lowering of emission of contaminants. This problem can be solved as a result of quality improvement of charge materials, as well as optimization of blast furnace equipment and technology [10–15]. Improvement of slag conditions is also one of the directions of blast furnace melting efficiency rise, providing both decrease of coke consumption and improvement of cast iron quality [16–18].

Slag is an accompanying product in each metallurgical process. From this point of view, it should provide minimal negative influence of the technical and economic indicators (TEI) of blast furnace practice; in this case, slag amount should be minimal and its properties (such as viscosity and melting temperature) should provide its high fluidity and minimal resistance to passage of gases [17, 18]. From other side, slag makes the main work for cast iron desulfurization in a blast furnace and sufficient slag amount is required for this purpose, as well as its high sulfide capacity [19–21], which increases with basicity rise.

Despite multiple researches devoted to this theme [16–21], the problem of improvement of slag conditions during blast furnace melting remains actual because the optimal slag parameters are determined by special charge operating conditions in blast furnaces. Thereby the problem of slag conditions optimization during blast furnace melting was solved in this research on the example of the blast furnace No. 2 of JSC "Ural Steel" with working volume 1,232 m^3.

The research object and initial data

To consider the influence of slag procedure on technical and economic indicators of a blast furnace melting, the results of blast furnace No. 2 operation during 2021–2023 are analyzed. This period is characterized by furnace operation with relatively permanent charge, while the periods of preventive and predictive maintenance works were excluded. The average parameters of the furnace operation and controlled indicators of the slag procedure are presented in the **Table 1**.

Results and discussion

The above-presented data testify that tha main furnace indicators varied essentially during the examined period. So, productivity changed within the range from 1797,1 to 2203.5 t/day with the average value 2012.5 t/day, while specific coke consumption changed from 401.0 to 457.7 kg/t with the average value 433.2 kg/t, what is connected with variations in operating conditions. Noted variability of the furnace operating conditions does not allow to evaluate adequately influence of the slag procedure on the firnace operating TEI. That's why influence of the slag procedure on the firnace operating TEI is evaluated by coke consumption and productivity, which were calculated for the furnace operating conditions in March 2021, taking into account [22].

Taking into account essential variation of MgO and Al_2O_3 content in slag, use of the simple basicity indicator B of CaO/SiO_2 does not provide the complete information about slag properties. Thereby the indicators B1 of summarized basicity of $(CaO+MgO)/SiO_2$ and B2 of complete basicity of $(CaO+MgO)/(SiO_2+Al_2O_3)$ were used for further analysis. Influence of these indicators on specific coke consumption is presented in the **Fig. 1**, which testifies that higher coke consumption is required with increase of slag basicity and, respectively, its amount. At the same time, use of summarized basicity B1 for analysis of influence of the slag procedure on

Table 1. The average parameters of the furnace operation and controlled indicators of the slag procedure

Parameters		The value during the period	
		range	average
Actual productivity, t/day		1797.1–2203.5	2012.5
Reduced productivity*, t/day		1605.4–2301.4	1910.2
Fe content in the ore part, %		54.6–61.6	57.4
Slag output, kg/t of cast iron		304.6–394.0	343.8
The part in the charge ore part, %	Pellets	18.1–61.6	40,2
	Sinter	36.3–81.9	58,3
Ore load, t/t of coke		3.5–4.2	3.85
Blowing parameters	Consumption, m^3/min	1773–2303	1984
	Pressure, MPa	0.294–0.347	0,324
	Temperature, °C	1059–1166	1118
	O_2 content, %	24.3–31.2	28,7
Actual coke consumption, kg/t		401.0–457.68	433.2
Reduced coke consumption, kg/t		390.3–475.6	444.2
Natural gas consumption, m^3/t		102.6–177.7	132.2
Chemical composition of slag, %:	SiO_2	40.4–44.9	41,9
	Al_2O_3	6.7–10.0	7,8
	CaO	41.4–46.1	43,7
	MgO	4.7–7.6	5,9
	FeO	0.26–0.58	0,39
	S	0.51–0.82	0,66
Basicity B = CaO/SiO_2, un.		1.002–1.098	1.058
Basicity B1 = $(CaO+MgO)/SiO_2$, un.		1.11–1.25	1.19
Basicity B2 = $(CaO+MgO)/(SiO_2+ Al_2O_3)$, un.		0.95–1.06	1.00
CaO/MgO, un.		5.45–9.38	7.49
Al_2O_3/SiO_2, un.		0.16–0.25	0.19
Slag output, kg/t of cast iron		325–368	343.8

* The value is calculated for the furnace operating conditions in March 2021

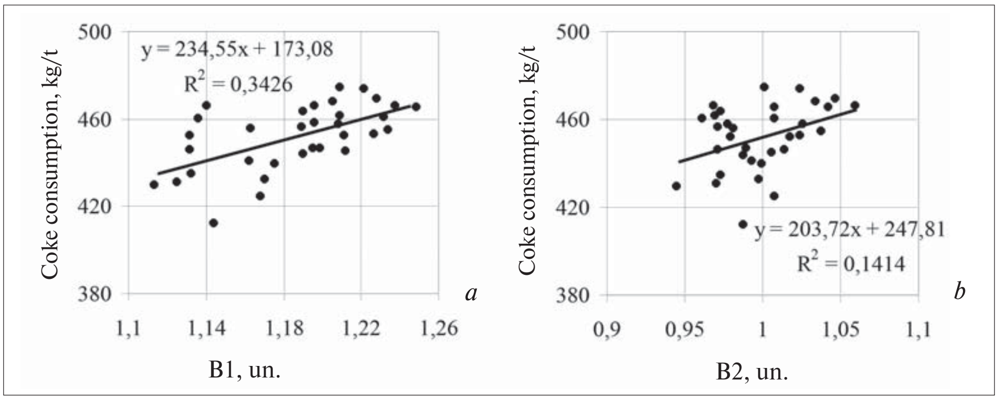

Fig. 1. Influence of summarized B1 (*a*) and complete B2 (*b*) basicity on the reduced coke consumption

coke consumption provides more adequate regression equation, with determination ration 0.34 un.

Influence of slag basicity indicators on productivity is presented in the **Fig. 2**. Lowering of productivity with rise of basicity is connected both with increase of slag amount and decrease of Fe amount in charge and with deterioration of gas dynamic conditions of blast furnace melting. In the same way as with coke consumption, the indicator B1 of summarized basicity describes influence of basicity on productivity with higher reliability.

Thus, slag basicity, which is adjusted via varying sinter basicity and relationship of sinter and pellets in charge, determines slag output and, respectively, provides influence on productivity and coke consumption. So, from the point of view of achieving high technical and economic indicators of blast furnace operation, slag procedure should be characterized by minimal basicity.

However, when choosing the slag basicity level, it should be taken into account that main positive slag work in the blast furnace practice concludes in cast iron desulfurization. For this purpose, both sufficient slag amount and its high sulfide capacity are required. Desulfurization woth in a blast furnace is evaluated by sulfur content in cast iron, sulfur distribution coefficient (Ls) and desulfurization degree.

Influence of the simple basicity indicator (B) on desulfurization results is presented in the **Fig. 3**, which displays that

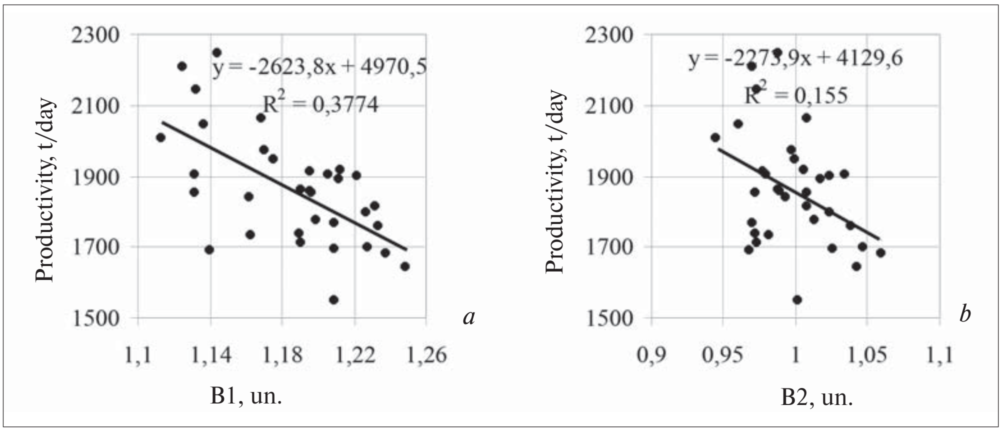

Fig. 2. Influence of summarized B1 (*a*) and complete B2 (*b*) basicity on the reduced productivity

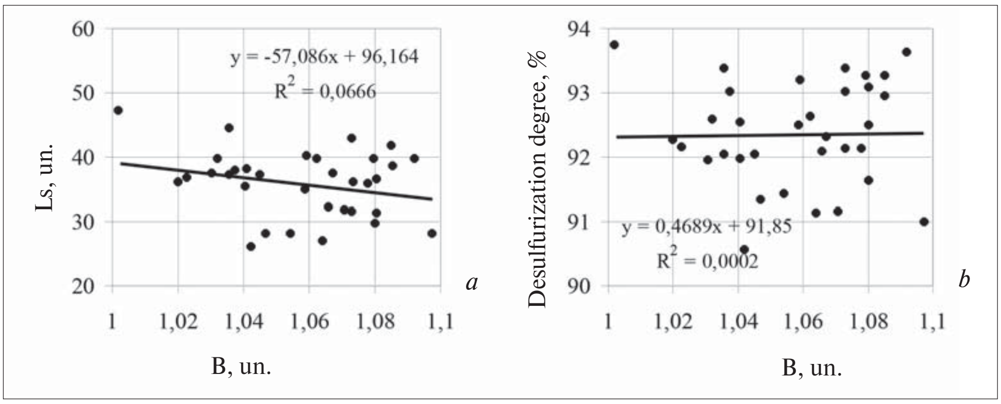

Fig. 3. Influence of simple basicity (B) on the sulfur distribution coefficient (*a*) and desulfurization degree (*b*)

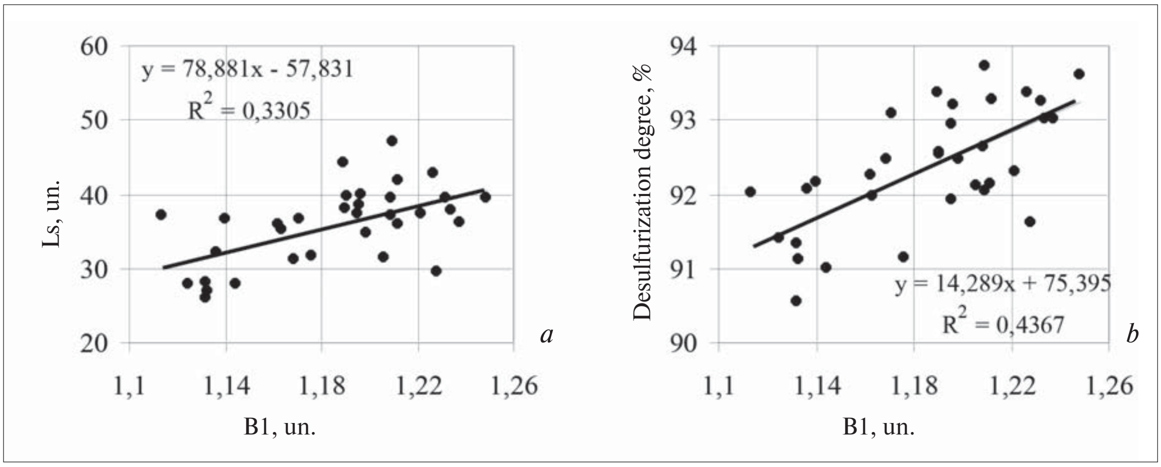

Fig. 4. Influence of summarized basicity (B1) **on the sulfur distribution coefficient** (*a*) **and desulfurization degree** (*b*)

the simple basicity indicator has no influence on cast iron desulfurization degree, while sulfur distribution coefficient decreases with increase of the B1 indicator.

However, this anomalous result is evidently connected with insufficient efficiency of the simple basicity indicator (B), which takes into account composition and sulfide slag capacity not completely. Use of the summarized basicity (B1) for evaluation of desulfurization results is presented in the **Fig. 4**. It provides more adequate picture, which corresponds to the theory of sulfur behaviour in a blast furnace and during blast furnace practice.

Thus, use of the simple basicity indicator (B) provides distorted results during analysis of the results of blast melting both by main parameters and desulfurization results in the conditions of unstable slag composition. It is expedient to apply the summarized (B1) or complete (B2) slag basicity in such conditions.

Summarized slag basicity as an integral indicator, which characterizes sulfide capacity, can be risen both as a result of increase of CaO and MgO content. It is known that CaO is more strong oxide in comparison with MgO; however, rise of CaO content increases melting temperature and viscosity of blast furnace slags, what in its turn deteriorates desulfurization conditions. At the same time, rise of MgO content in slag up to 10–12 % increases fluidity and stability of blast furnace slags [23–25] and supports improvement of desulfurization conditions and results. More important role of MgO in desulfurization results comparing with CaO is confirmed by influence of CaO/MgO relation; its decrease leads to improvement of the results (**Fig. 5**).

So, from the point of view of improving the conditions and results of metal desulfurization, it is expedient to correct slag composition, meaning rising MgO content up to 8–10 % with saving the value of summarized basicity (B1) at the level 1.16–1.18 un. For this purpose it is recommended to rise MgO content in sinter [26–28] with simultaneous correction of CaO addition with charge as a result of lowering sinter basicity in relation to CaO/SiO_2 or increase of the part of pellets. To keep the value of summarized basicity at the level 1.16–1.18 un. with MgO content up to 8–10 % and current silica content in slag at the level 41–42 %, it is necessary to decrease CaO content from the current 43–44 % to 39–40 %, with achieving the level of simple slag basicity (B) to 0.95 un. This level provides lowered melting temperature and viscosity of slag [20–25].

Besides MgO, the Al_2O_3/SiO_2 relation in slag provides substantial influence on slag physical properties, i.e. on its viscosity and melting temperature (**Fig. 6**).

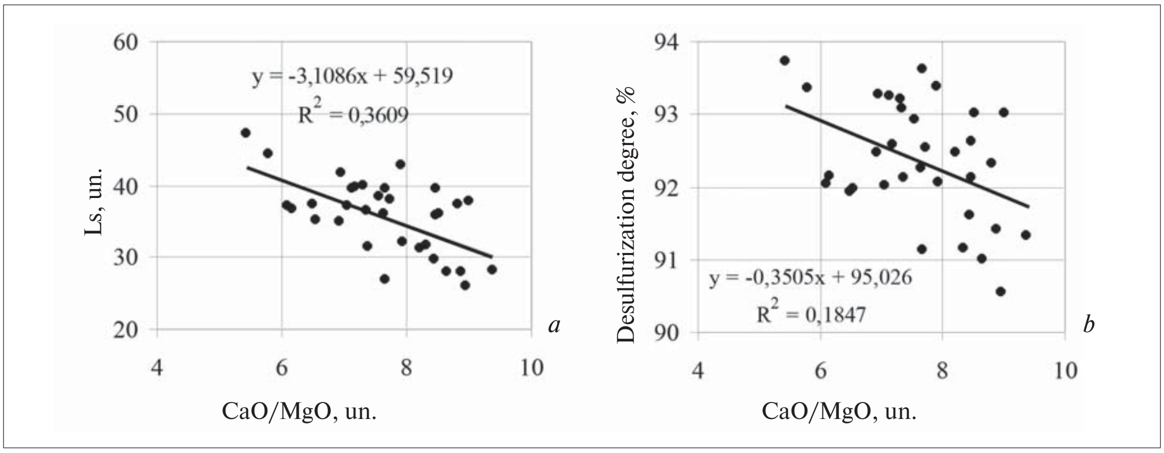

Fig. 5. Influence of CaO/MgO relation on the sulfur distribution coefficient (*a*) **and desulfurization degree** (*b*)

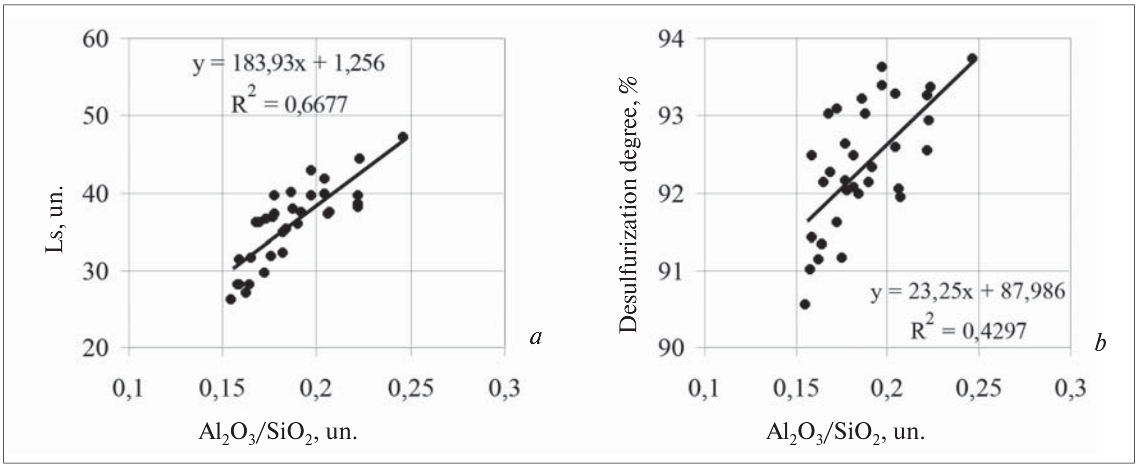

Fig. 6. Influence of Al_2O_3/SiO_2 relation in slag on the sulfur distribution coefficient (*a*) and desulfurization degree (*b*)

The data presented in the Fig. 6 testify that increase of Al_2O_3/SiO_2 relation from 0.15 to 0.25 un. improves desulfurization results, thereby Al_2O_3/SiO_2 relation equal to 0.20–0.25 un. can be considered as a favourable one for the examined charge conditions. In order to obtain slag with such Al_2O_3 and SiO_2 relation at the current silica content 41–42 %, it is required to provide alumina content in slag at the level 9–10 %. Positive influence just of such level of alumina content in slag was noted also in the technical literature [25, 29, 30].

Current and rational indicators of the slag procedure, which provide improvement of TEI for the furnace operation and cast iron quality, are presented in the **Table 2**.

When keeping the suggested slag procedure, we can wait for decrease of slag amount, in addition to improvement of the conditions and results of desulfurization. In general, it allows to decrease coke consumption and provide the conditions for the blast furnace productivity rise, together with improvement of slag physical properties (viscosity and fluidity).

Conclusion

The results of analysis of production data of the blast furnace No. 2 operation during the period 2021–2023 displayed that the slag procedure should be characterized by minimal basicity, providing achievement of the preset quality of cast iron, from the point of view of obtaining the optimal TEI of blast furnace operation.

To improve the conditions and results of metal desulfurization, it is expedient to correct slag composition directed to increase MgO content up to 9–10 % with lowering the level of simple slag basicity to 0.95 un. and saving the value of summarized basicity at the level 1.16–1.18 un. Additionally, it is expedient to provide Al_2O_3/SiO_2 relation at the level 0.20–0.25 un. When keeping the suggested slag procedure, we can wait decrease of slag amount in addition to improvement of the conditions and results of desulfurization. Together with improvement of slag physical properties (viscosity and fluidity), it allows to decrease coke consumption and provides conditions for blast furnace productivity rise.

Table 2. Current and rational indicators of the slag procedure

Indicator	Examined period	Optimal values
Slag procedure		
CaO, %	41.4–46.1 / 43.7	39–40
SiO_2, %	40.4–44.9 / 41.9	41–42
MgO, %	4.7–7.6 / 5.9	9–10
Al_2O_3, %	6.7–10.0 / 7.8	9–10
CaO/MgO, un.	5.45–9.38 / 7.49	4.5
Al_2O_3/SiO_2, un.	0.16–0.25 / 0.19	0.20–0.25
Basicity B = CaO/SiO_2, un.	1.0–1.1 / 1.06	0.95
Basicity B1 = $(CaO+MgO)/SiO_2$, un.	1.11–1.25 / 1.19	1.16–1.18
Basicity B2 = $(CaO+MgO)/(SiO_2+Al_2O_3)$, un	0.95–1.06 / 1.00	0.96
Slag output, kg/t	325–368 / 343.8	320–340 / 330
Technical and economic indicators		
Furnace productivity, t/day	1797.1–2203.5 / 2012.5	2250
Coke consumption, kg/t	401.0–457.7 / 433.2	420
Sulfur content [S], %	0.015–0.024 / 0.019	0.014–0.016

Besides the above-mentioned recommendations, directed on optimization of the slag procedure, it is necessary to use the indicators of summarized or complete basicity during analysis of blast furnace operating parameters and results of desulfurization in the conditions of instability of charge and slag composition. These indicators provide more objective results, otherwise simple basicity.

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