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Reduction of specific coke consumption in blast furnace by impact on thermal reverse zone

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Abstract. At the blast furnace of PJSC "Magnitogorsk Metallurgical Plant" (MMK), the specific consumption of coke was reduced by impact on thermal reverse zone (TRZ) by increasing the consumption of natural gas above 120 m^3/t of cast iron under conditions of increased reactivity and reduced hot strength of coke. In the first pair of periods, an increase in CRI from 38.4 to 39.3 % with a decrease in CSR from 36.3 to 34.6 % was accompanied by an increase in the ratio of natural gas consumption and total oxygen entering the furnace from 0.43 to 0.45 by increasing the specific gas consumption from 123.2 to 133.5 m^3/t of cast iron. The set of actions increased the TRZ length towards the blast-furnace mouth by 1.9 % with its unchanged location along the lower part. Reducing the heat consumption in the TRZ increased the temperature difference between gas and materials there by an average of 36 °C. In the second pair of periods, the consumption of natural gas was 143.9 m^3/t of cast iron with a decrease in the oxygen content in the blast from 27.6 to 27.0. They were accompanied by the following changes in the processes under consideration: an increase in the length of the TRZ towards the blast-furnace mouth by 2.6 % and the distance from the tuyere hearth by 3.4 %, an increase in the degree of carbon reduction from 32.0 to 33.3 %, an insignificant (on average 0.3 °C) increase in the temperature difference of gas and materials in the TRZ. In the first pair of periods, reduction in the coke specific consumption was 4.7 kg/t of cast iron with an increase in furnace productivity by 27 t/day. Conditions and course of the processes of the second pair ensured a decrease in the coke specific consumption by 1.6 kg/ton of cast iron and led to a decrease in cast iron production by 41 t/day.

Keywords: blast furnace smelting, coke, cast iron, natural gas, heat transfer

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Снижение удельного расхода кокса в доменной печи воздействием на зону замедленного теплообмена

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Аннотация. На доменной печи ПАО «Магнитогорский металлургический комбинат» удельный расход кокса снижали воздействием на зону замедленного теплообмена (ЗЗТ), увеличивая потребление природного газа выше 120 м^3/т чугуна в условиях повышенной реакционной способности и пониженной горячей прочности кокса. В первой паре периодов рост CRI от 38,4 до 39,3 % с уменьшением CSR от 36,3 до 34,6 % осуществили одновременно с увеличением отношения расходов природного газа и всего поступающего в печь кислорода от 0,43 до 0,45 путем повышения удельного расхода газа от 123,2 до 133,5 м^3/т чугуна. Применение комплекса действий увеличило протяженность зоны замедленного теплообмена в сторону колошника на 1,9 % при неизменном ее расположении по нижней части. Уменьшение потребления тепла в ЗЗТ увеличило разность температур газа и материалов в среднем на 36 °С. Во второй паре периодов потребление природного газа довели до 143,9 м^3/т чугуна при снижении содержания кислорода в дутье с 27,6 до 27,0. Это сопровождалось следующими изменениями рассматриваемых процессов: увеличением протяженности ЗЗТ в сторону колошника на 2,6 % и отдаленности от фурменного очага на 3,4 %; повышением степени восстановления углеродом с 32,0 до 33,3 %; незначительным (в среднем 0,3 °С) ростом разности температур газа и материалов в зоне ЗЗТ. В первой паре периодов уменьшение удельного расхода кокса составило 4,7 кг/т чугуна с повышением производительности печи на 27 т/сут. Условия и ход процессов второй пары обеспечили уменьшение удельного расхода кокса на 1,6 кг/т чугуна и привели к снижению производства чугуна на 41 т/сут.

Ключевые слова: доменная плавка, кокс, чугун, природный газ, теплообмен

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Introduction

The question of determining the rational parameters for combined blast during blast furnace smelting, in alignment with the developmental goals of ferrous metallurgy, remains pertinent [1 – 4]. The simultaneous utilization of reducing additives in the form of natural gas and pulverized coal fuel, with the ratio of their flow rates to that of the process oxygen ranging from 0.9 to 1.2, has contributed to the stabilization of theoretical combustion temperature and other process parameters. The degrees of direct and indirect reduction are notable factors in these processes [5]. Upon analyzing the operation of blast furnaces at PJSC "Magnitogorsk Metallurgical Plant" (MMK), the significant role of the reactivity index and coke strength after the reaction was further confirmed [6]. In the context of blast furnaces in Japan, it becomes imperative to estimate the initial gasification temperature of carbonaceous materials as the thermal reverse zone (TRZ) takes shape. The study presented in reference [7] delves into the injection of hydrogen as a reducing agent, replacing carbon, with the aim of mitigating CO_2 oxide emissions. Simultaneously, this approach enhances the efficiency of reduction through CO gaseous oxide. The experiment demonstrated that the reduction of CO_2 oxide emissions from the blast furnace is achieved within a hydrogen concentration range of up to 20 %.

The papers [8 – 11] underscore the vital role of mathematical models due to the scarcity of information on process parameters such as temperature, pressure, and reduction levels along height of the furnace. The processes that arise and evolve within the TRZ, leading to a substantial increase in iron reduction, are pivotal elements within these evolving mathematical models. These models are currently in development and implementation. The kinetic modeling, encompassing an evaluation of the thermal reverse zone's impact on blast furnace operations, is congruent with this perspective [7]. An investigation was conducted to assess the influence of material temperature upon charging into the furnace, their reductibility, and gas pressure at the furnace's mouth on the outcomes of blast furnace smelting. The findings revealed that as gases become more actively utilized within the furnace, the temperature at the onset of the thermal reverse zone decreases [9]. The paper [12] has illustrated that the specific consumption of coke diminishes with an increase in the duration of time the charged materials spend within the TRZ. A noteworthy reduction of 3.6 kg per ton of cast iron was achieved [13] by mitigating heat outflow from the region where $W_{ch}/W_g \geq 1$ to the area where $W_{ch}/W_g < 1$, with W_{ch} and W_g representing the heat capacities of charge and gas flows, respectively. In the thermal reverse stage ($W_{ch} \approx W_g$), the temperature registered a decline of 2.5 °C, while the temperature differential between the gas and the charge contracted by 1.3 °C.

An evaluation of rational approaches concerning blast furnaces at MMK has unveiled the substantial significance of coke reactivity index and post-reaction strength in relation to the adjustment of natural gas consumption [6]. This complements prior explorations of these phenomena [14 – 19]. Theoretical and experimental investigations have contributed to the recognition of the importance of temperature boundaries distinguishing between indirect, mixed, and direct reduction regions [14]. The values characterizing these boundaries exhibit interrelationships with the rates of oxide reduction by gases such as CO and H_2, as well as the rates of carbon gasification by gaseous reduction products, CO_2 and H_2O [16].

In laboratory experiments, where the charge was maintained under identical temperature and time conditions as those in the upper section of the blast furnace shaft, a comparison was conducted between charcoal and coke concerning their influence on the degree of sinter reduction by a gas mixture comprising 29 % CO, 2 % H_2 and 60 % N_2 [16]. The results obtained were as follows:

Temperature, °C	600	700	750	800	850	900
Heating time, min	37	72	107	132	150	165
Reduction degree by oxygen removal, %:						
when using charcoal	2	8	17	24	32	67
when using coke	1.5	6	15	20	22	25

Based to these data, at temperatures corresponding to intense heat exchange in the upper section of the furnace (up to 750 °C), the reduction degree exhibited only a marginal increase, with fuel reactivity nearly unchanged. Simultaneously, the flue gas composition contained approximately 10.4 – 10.8 % CO_2. At temperatures corresponding to the initiation and progression of the thermal reverse zone (above 750 °C), a portion of CO_2 oxide engaged in interactions with carbon from the fuel, leading to the formation of CO oxide. The formation of CO oxide by charcoal, a fuel with a higher reactivity index, contributed more significantly to the enhancement of sinter reduction compared to its formation by coke. This effect assumed considerable importance in the optimization of the blast furnace process as natural gas consumption increased [18].

Experiments that involved the examination of coke samples extracted from the pilot blast furnace unveiled four different reactivity pathways. The outcome of these pathways includes the potential reduction of coke-specific consumption and the augmentation of blast intensity. Furthermore, the ability of coke carbon to react with CO_2 oxide was also observed to increase [20 – 22]. In practical applications, these findings can be implemented by incorporating machine vision systems for both the upper and lower sections of the blast furnace [23 – 29]. Additionally, they align with concepts associated with the electronic theory of iron reduction from oxides [30; 31].

Materials and methods

Using the insights gathered from the works [1 – 31], we successfully reduced coke-specific consumption within a blast furnace with a production capacity of 1370 m^3. This reduction was achieved by strategically manipulating the thermal reverse zone, primarily through an increase in natural gas-specific consumption, while concurrently adjusting the coke reactivity index (CRI) and coke strength after reaction (CSR) in opposite direction. The most important operational characteristics of the furnace are depicted in Fig. 1 – 4.

The vertical pressure behavior (active weight P_a) of materials along both the height and the cross-section of the furnace is presented in Fig. 1 and 2.

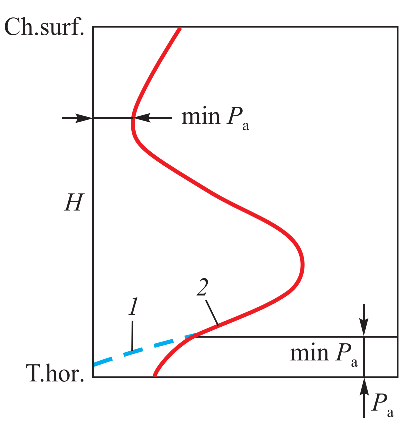

Fig. 1. Vertical pressure of materials from charge surface (Ch. surf.) along the furnace height (*H*) to tuyeres' horizon (T.hor.):
1 – over loose part of tuyere hearth; *2* – on average in the furnace

Рис. 1. Вертикальное давление материалов от поверхности шихты (Ch. surf.) по высоте печи (*H*) до горизонта фурм (T.hor.):
1 – над рыхлой частью фурменного очага; *2* – в среднем по печи

Average temperature trends along the height of the blast furnace are depicted in Fig. 3, while those concerning temperature distribution by radius are illustrated in Fig. 4 and 5. These figures are constructed based on the findings and insights from the referenced papers [14; 17; 22].

When temperatures fall below the range of 850 – 900 °C, it is observed that the heat capacity of the gas flow surpasses that of the charge flow ($W_g > W_{ch}$), while the W_{ch}/W_g ratio

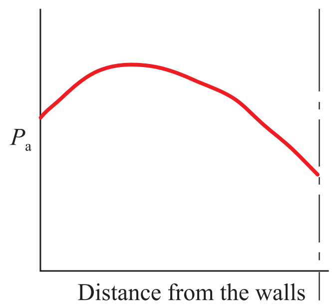

Fig. 2. Vertical pressure of materials from lining to the blast furnace axis

Рис. 2. Вертикальное давление материалов от футеровки до оси доменной печи

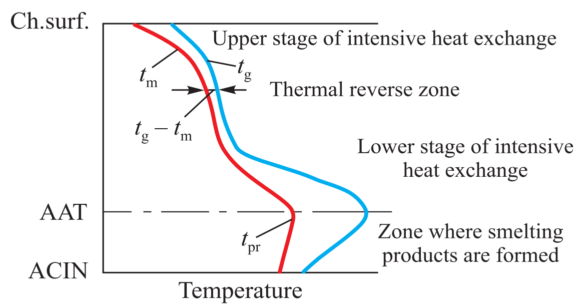

Fig. 3. Scheme of temperature changes of materials (t_m) and gases (t_g) along the blast furnace height:
AAT – axis of the air tuyeres; ACIN – axis of the cast iron notch;
t_{pr} – temperature of the smelting products

Рис. 3. Схема изменения температур материалов (t_m) и газов (t_g) по высоте доменной печи:
AAT – ось воздушных фурм; ACIN – ось чугунных леток;
t_{pr} – температура продуктов плавки

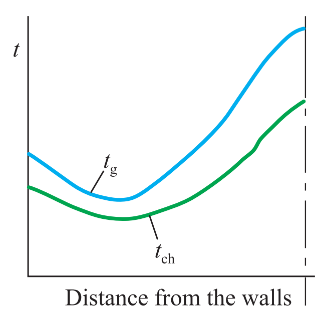

Fig. 4. Diagram of changes in temperatures of the charge (t_{ch}) and gases (t_g) from walls to axis of the blast furnace

Рис. 4. Схема изменения температур шихты (t_{ch}) и газов (t_g) от стен до оси доменной печи

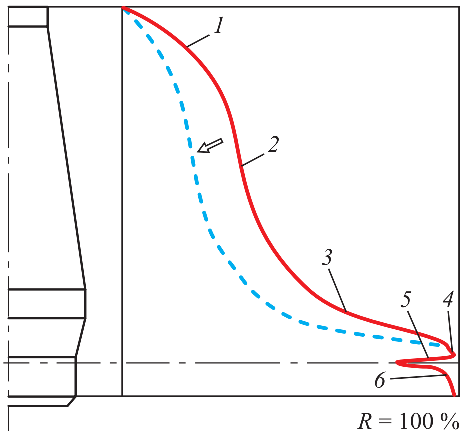

Fig. 5. Nature of changes in reduction degree along the blast furnace height

Рис. 5. Характер изменения степени восстановления по высоте доменной печи

remains within the range of 0.7 – 0.9. This surplus heat in the upper heat exchange phase, not absorbed by the charge, finds application in low-temperature processes without necessitating an increase in the quantity of coke introduced into the furnace. Notably, no additional coke is required for moisture evaporation.

Fig. 5 illustrates the portion of oxygen from all oxides extracted from the charged materials by various reducing agents. In the figure: *1* – accelerated reduction occurring in the upper part of the blast furnace, which is attributed to the low stability of the chemical bond of Fe_2O_3 and Fe_3O_4; *2* – reduction taking place in the conditions of the thermal reverse zone, which are highly conducive to reactions $FeO + CO = Fe + CO_2$ and $FeO + H_2 = Fe + H_2O$, with each unit of temperature change significantly influencing the reduction process; *3* – accelerated reduction due to the intensity of its direct progression ($FeO + C = Fe + CO$); *4* – slower reduction occurring as the process reaches its conclusion, with only a few unreduced oxides remaining; *5* – a decrease in the reduction degree due to the oxidation of smelting products in tuyere hearths; *6* – rapid reduction of elements, mainly iron, previously oxidized in tuyere hearths. The solid line in the figure corresponds to modern blast furnace smelting conditions, while the dashed line signifies potential advancements in blast furnace smelting technology.

Results and discussion

At the blast furnace of MMK, the reduction in coke-specific consumption was achieved by elevating the utilization of hydrogen and augmenting the degree of iron reduction from FeO oxide. This was accomplished by influencing the thermal reverse zone, leading to an increase in natural gas consumption exceeding 120 m^3/t of cast iron. The study focused on two paired periods: *I* and *II* (the first pair) and *III* and *IV* (the second pair). The periods within each pair were contiguous, primarily spanning seven days each.

During period *I* of the first pair, under the initial conditions, the natural gas flow rate stood at 123.2 m^3/t of cast iron. When the blast contained 27.2 % of oxygen, the ratio of gas and oxygen consumption equated to 0.43 (Table 1). In the second pair (base period *III*), these values increased to 135.8 m^3/t of cast iron; 27.6 % oxygen and a ratio of 0.47, respectively.

In both pairs of periods, several key parameters experienced growth, including the mass of the gas-air mixture per tuyere, its kinetic energy of efflux, and the extent of the loose portion of the tuyere hearth. Notably, these parameters exhibited more pronounced changes in the first pair of periods.

The coke strength after reaction CSR under the baseline conditions of the first pair of periods amounted to 36.3 %, with a reactive index (CRI) of 38.4 %. During the renewed smelting mode, CRI increased by 0.9 % to reach 39.3 %. In the basic conditions of the second pair, CSR was 39.5 %, and CRI was 39.1 %, with a variation reducing CRI to 37.8 % (Table 2).

In period *II*, as compared to period *I*, CSR decreased from 36.3 to 34.6 %, and CRI increased from 38.4 to 39.3 %. This change resulted in an increase in the ratio of natural gas consumption to the total oxygen entering the furnace, rising from 0.43 to 0.45. The gas-specific consumption also increased from 123.2 to 133.5 m^3/t of cast iron. Additionally, the oxygen content in the blast increased from 27.2 to 28.4 %. These alterations facilitated an increase in hydrogen reduction from 31.9 to 37.2 % (Table 3) and an enhancement in its utilization, from 45.3 to 48.8 %. Meanwhile, the length of the TRZ increased towards the blast furnace mouth by 1.9 %, while its position at the bottom remained unchanged. A significant reduction in carbon reduction, from 30.7 to 24.4 %, led to a decrease in heat consumption within the TRZ, resulting in an average temperature difference $t_g - t_{ch}$ (Fig. 3) increasing by 36 °C.

In period *IV*, in comparison to period *III*, the main factors pertaining to smelting conditions underwent the following changes:

– an increase in natural gas consumption from 135.8 to 143.9 m^3/t of cast iron;

– a decrease in the oxygen content in the blast from 27.6 to 27.0 %;

– an increase in the ratio of natural gas consumption to the total oxygen entering the furnace from 0.47 to 0.51;

– a decrease in CRI from 39.1 to 37.8 %;

– an increase in CSR from 39.5 to 40.2 %.

As a result, several changes in the studied processes during period *IV*, compared to period *III*, were observed:

– an increase in the length of the TRZ towards the blast-furnace mouth by 2.6 % and the distance from the tuyere hearth by 3.4 %;

– an increase in the degree of carbon reduction from 32.0 to 33.3 %;

Table 1

Parameters of the blast and blast-furnace gas

Таблица 1. **Параметры дутья и колошникового газа**

Indicator	Indicator value in the period			
	I	*II*	*III*	*IV*
Consumption of:				
blast, m^3/t of cast iron	1044	1056	1053	1087
natural gas, m^3/t of cast iron	123.2	133.5	135.8	143.9
Hot blast pressure, kPa	271	272	269	272
Blast temperature, °C	1155	1152	1154	1154
Water vapor flow rate, g/m^3	3.13	3.72	2.21	1.99
Oxygen content, %	27.2	28.4	27.6	27.0
Ratio of natural gas consumption to total oxygen consumption	0.43	0.45	0.47	0.51
Degree of utilization, %:				
CO	42.6	42.5	42.8	42.0
H_2	45.3	48.8	43.5	44.3
Gas temperature in gas vents, °C	235	246	217	233
Blast-furnace gas pressure (exc.), kPa	141.8	142.2	141.9	142.0
Actual stock line, м	1.73	1.87	1.69	1.65
Gas temperature along the radius, °C:				
at the periphery (T_{per})	247	263	233	264
in the “ore ridge” (T_r)	213	234	196	218
in the center of the furnace (T_c)	384	370	390	410
Dynamic gas head on the empty section of the furnace under operating conditions in terms of temperature and pressure, n/m^2:				
in the blast furnace mouth	2.05	2.26	2.12	2.25
in the belly	0.98	1.04	1.05	1.08
in the top part of the hearth	1.30	1.45	1.39	1.42

Table 2

Quality indicators of the charge materials

Таблица 2. **Показатели качества шихтовых материалов**

Indicator	Indicator value in the period			
	I	*II*	*III*	*IV*
Content of 0 – 5 mm fraction in sinter, %	8.47	9.34	8.35	8.23
Ash content in coke, %	12.57	12.64	12.52	12.58
Coke basis strength, %:				
M10	8.13	8.11	8.06	7.83
M25	87.62	87.82	87.47	87.67
Coke strength after reaction CSR, %	36.3	34.6	39.5	40.2
Coke reactivity index CRI, %	38.4	39.3	39.1	37.8

– a slight, albeit insignificant, increase in the temperature difference $t_g - t_{ch}$ (Fig. 3), averaging only 0.3 °C.

The key thermal performance characteristics accompanying these alterations are detailed in Table 4.

In terms of the recorded parameters, the temperature in the axial zone of the blast-furnace mouth decreased by 14 °C in period *II* when compared to period *I*, and conversely, it increased by 20 °C in period *IV* when compared to period *III* (Table 1).

The series of modifications within the processes, encompassing the ratios T_{per}/T_g, T_{per}/T_c, T_c/T_g, resulted in a reduction in coke-specific consumption in period *II*

Table 3

Reduction distribution indicators

Таблица 3. **Показатели распределения восстановления**

Indicator	Indicator value in the period			
	I	*II*	*III*	*IV*
Ratio of utilization rates H_2 and CO	1.06	1.15	1.02	1.05
Degree of Fe reduction from FeO by different reducing agents, %:				
carbon	30.7	24.4	32.0	33.3
carbonic oxide CO	37.4	38.4	34.6	30.8
hydrogen	31.9	37.2	33.4	35.9

Table 4

Heat consumption indicators

Таблица 4. **Показатели потребления тепла**

Indicator	Indicator value in the period			
	I	*II*	*III*	*IV*
Ratio of heat capacities of charge and gas flows:				
in the upper stage of intensive heat exchange	0.756	0.742	0.777	0.757
in the lower stage of intensive heat exchange	1.763	1.763	1.715	1.656
Total heat consumption for all processes in the zone determining coke consumption (Q_{Σ}), MJ/t of cast iron	2663	2759	2650	2643

Table 5

Main technological indicators of the furnace

Таблица 5. **Основные технологические показатели работы печи**

Indicator	Indicator value in the period			
	I	*II*	*III*	*IV*
Duration of the period, days	7	6	7	7
Specific consumption of dry coke, kg/t of cast iron	434.9	430.2	437.5	435.9
Ratio of specific consumption of solid (C_{SCP}) and gaseous (NG_{SP}) fuels, kg/m^3	3.53	3.15	3.22	3.06
Capacity, t/day	3467	3490	3512	3471
Consumption, kg/t of cast iron:				
raw materials	1694	1681	1678	1665
including				
quartzite	2.4	34.8	0	44.2
manganese ore	23.7	18.1	23.9	13.0
Share of pellets from IORM, %	34.1	31.1	37.7	39.6
Ore load, t/t	3.895	3.889	3.835	3.782
Fe content in the charge, %	57.32	57.77	57.86	58.32

compared to period *I* from 434.9 to 430.2 kg/t of cast iron, while in period *IV*, in comparison to period *III*, from 437.5 to 435.9 kg/t of cast iron (Table 5). During the first pair of periods, furnace productivity increased by 27 t/day; however, the conditions and progression of the processes during the second pair led to a decrease in cast iron production by 41 t/day (Table 5).

The shift of the coke carbon gasification process in period *II*, in comparison to period *I*, led to a 6.9 % reduction in the factor of charge and its product's resistance to gas movement in the lower part of the bosh (Fig. 1, the region of minimal P_a value). This shift also facilitated smelting with an 11.5 % increase in lift force of the gas flow (Table 1). The shift of the coke carbon gasification region in period *IV* compared to period *III* to the region of lower temperatures led to a decrease in the coke specific consumption and the processes rate, resulting in decline of the furnace output (Table 5).

Conclusions

The parameters, such as length, height location, temperature, and the temperature difference between rising gases and descending materials within the blast furnace's TRZ, exert significant influence on coke-specific consumption. The formation of the TRZ is contingent on various factors, including the coke reactivity index (CRI), coke strength before reaction (CSR), natural gas consumption, and process oxygen consumption.

At the blast furnace of MMK, a series of smelting operations were conducted, categorized into two pairs of periods: the first pair serving as the base period and the second as the experimental period.

The first pair of periods witnessed an increase in natural gas consumption, rising from 123.2 to 133.5 m^3/t of cast iron. The length of the TRZ extended towards the blast furnace mouth by 1.9 %, maintaining its position at the bottom unchanged. Simultaneously, the temperature gradient between the gas and materials surged by 36 °C. Conversely, in the second pair of periods, natural gas consumption increased from 135.8 to 143.9 m^3/t of cast iron. The TRZ expanded towards the blast furnace mouth by 2.6 %, and the distance from the tuyere hearth extended by 3.4 %. However, the temperature difference between the gas and materials within the TRZ registered a negligible increase, averaging just 0.3 °C.

In the first pair of periods, a reduction in coke-specific consumption by 4.7 kg/t of cast iron was achieved, resulting in a notable increase in furnace productivity by 27 t/day. However, in the second pair, coke-specific consumption decreased by 1.6 kg/t of cast iron, leading to a decrease in cast iron production by 41 t/day.

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S. K. Sibagatullin – organization of the research, conducting calculations, establishing the interconnections of blast-furnace process course, analysis of the research results.
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