Sintering process with gaseous fuel injection into the sintered layer

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Abstract

This paper presents the results of laboratory experiments to study the effect of the consumption of gaseous fuel (natural gas) supplied into a sintered charge layer on sintering process indicators and sinter quality under the charge conditions of the Ural Steel Company at charge layer heights of 350 to 500 mm.

It was established that an increase in the consumption of natural gas supplied to the sintered charge layer in the range from $3 \, m^3/t$ to $7 \, m^3/t$ of sinter increases the vertical sintering rate, yield, specific productivity, and strength properties of the sinter. The benefit of supplying gaseous fuel to the layer is due to improvement in the temperature-time conditions of sintering, which increases the degree of involvement of the charge ore in the processes of melt formation and ensures a more complete use of solid fuel at lower consumption. The efficiency of supplying gaseous fuel to the sintered charge layer increases substantially with increasing sintered layer height because of a decrease in the proportion of the upper part of the sinter, which is formed under less favorable thermal conditions.

According to the totality of indicators, considering the cost of natural gas, its optimal consumption in the charge conditions of the Ural Steel Company is $3.0 \, m^3/t$ of sinter, which ensures the maximum increase in sintering indicators and sinter quality compared with traditional sintering technology.

Keywords Agglomeration · Layer of sintered charge · Thermal conditions of sintering · Gaseous fuel · Height of sintered layer

Introduction

The combustion of solid fuel in a sintered layer, which determines the essence of the sintering process, affects its results, the sinter quality [1–3], and the environmental friendliness of production. Therefore, increasing sintering process efficiency, primarily toward reducing fuel consumption, pertains to all metallurgical plants.

Increasing the sinter strength and **reducibility** helps reduce the specific consumption of solid fuel in cast iron smelting and sintering production. A main condition for simultaneously increasing the sinter strength and reducibility is the creation of favorable temperature and time conditions in the liquid-phase sintering zone, ensuring complete involvement of the agglomerated charge in the processes of melt formation and obtaining a ferrite-silicate structure of the sinter with a minimum amount of glassy phases and FeO. The favorable temperature range for ferrite-silicate **bonding phases** formation without the development of hematite dissociation processes is considered to be from 1200 to 1400 °C [1, 4–6]; however, its maintenance in the

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combustion zone over the entire height of the sintered charge layer is problematic because of the uneven thermal conditions of sintering across layer height caused by the recirculation of sinter heat from the upper layers to the lower ones [1, 2]. This process results in the production of a low-strength, poorly sintered upper layer, up to 50–100 mm thick, formed under less favorable thermal conditions, as well as the formation of a remelted, low-porosity, **high-FeO content** lower part of the sinter [1, 2].

Many options have been developed to reduce the thermal unevenness of sinter formation along the height of the sintered charge layer, including the following approaches:

– a redistribution of solid fuel along the layer height [1, 2, 7–9];
– external heat treatment of the **sinter cake** in various ways [1, 2, 10–14];
– a supply of gaseous fuel to the sintered charge layer [15–19], ensuring an expansion of the high-temperature combustion zone.

Among the considered methods for equalizing temperature and thermal conditions along the height of the sintered charge layer, one of the most practical options for improving the thermal conditions of sintering without the need for deep modernization of production is to supply gaseous fuel to the sintered charge layer.

The results of laboratory and industrial experiments by Russian researchers on the joint combustion of solid and gaseous (combined) fuel in a layer of agglomerated charge [15, 19] confirm that a supply of gaseous fuel to the layer of sintered charge, particularly at the initial stage of sintering, makes it possible to reduce coke breeze consumption and ensures a larger yield by creating more favorable temperature and time conditions for sinter formation in the upper part of the sintered mass. However, despite its obvious advantages, the introduction of this technology at Russian metallurgical plants is obviously hampered by the high explosion hazard of this method. At the same time, considering the level of technological development, including the automation of modern production, compliance with safety measures when supplying gaseous fuel to the sintered charge layer is a completely solvable problem, which is confirmed by positive international experience in the use of agglomeration technology with the introduction of natural gas (NG) and other fuel gases of various compositions and origins (NG, coke oven, and blast furnace gases, as well as their mixtures) into the sintered charge layer [16–18].

Summarizing the results of numerous studies (laboratory and industrial) enables us to state that the supply of gaseous fuel into the sintered charge layer, which ignites when heated to 450–600 °C (depending on the composition), not only accelerates the charge heating and ensures reduction in **coke breeze** consumption but also creates more favorable temperature-time parameters of the sintering process, expanding the high-temperature zone of liquid-phase sintering (1200–1400 °C). In this case, the consumption of gaseous fuel must be selected individually depending on the fuel properties and the component composition of the agglomerated charge, considering the possible formation of self-igniting gas-air mixtures.

In this work, the problem of determining the rational consumption of gaseous fuel supplied to a layer of sintered charge was solved using the example of the use of NG while sintering a agglomerat charge based on magnetite ores and concentrates of the Kursk Magnetic Anomaly (KMA), which is typical for the operating conditions of the sintering shop of the Ural Steel Company.

Experimental technique

The studies were performed in the Ural Steel Company metallurgical laboratory, which is equipped with a pelletizing drum (diameter 0.6 m, length 1.2 m) and a sinter pot (diameter 210 mm; layer height up to 500 mm; vacuum up to 20 kPa). Materials used for sinter production at the Ural Steel Company (as of 2022), namely, concentrate from the Lebedinsky Mining and Processing Plant (LebMPP), sinter ores from the Mikhailovsky Mining and Processing Plant (MMPP) and the Bakal Ore Management Department (BOMD), limestone from the Akkermanovskoye deposit, and coke breeze from the coke-chemical production of the Ural Steel Company, were used as charge components.

To achieve the study aim, based on the information obtained from the scientific and technical literature on the issue of supplying gaseous fuel to a sintered mixture layer, a set of laboratory experiments was planned, involving five series of experiments:

– series No. 1 with standard technology without supplying gaseous fuel to the layer of sintered charge (base) at a layer height of 350 mm, which is characteristic of the operating conditions of the sintering shop of the Ural Steel Company;
– series Nos. 2–4 with NG feeding into the sintered charge layer at specific flow rates of $3 \, m^3/t$, $5 \, m^3/t$, and $7 \, m^3/t$ (with a calorific value of $41 \, MJ/nm^3$) and a layer height of 350 mm;
– series No. 5 with a supply of NG to the sintered charge layer (optimal consumption according to the results of series Nos. 2–4) at a charge layer height of 500 mm, the maximum height according to the technical conditions of the laboratory installation and typical for modern sintering industries.

The experimental charge composition was calculated to obtain an agglomerate with a basicity of $CaO/SiO_2 =$ 1.6 units and a content of 1.6% MgO (average sinter values of the Ural Steel Company for 2022), with a constant ratio of concentrate and KMA ore and BOMD ore consumption, providing the required level of MgO. The consumption of solid fuel under basic conditions was selected experimentally from the condition of obtaining a regulated level of FeO content in the agglomerate of 11–13%. **Coke breeze** consumption under experimental conditions was further reduced by an amount equivalent to 120% of the thermal energy obtained from combusting gaseous fuel (considering the calorific value of the coke breeze of 27.1 MJ/kg). The coefficient of coke replacement by 1.2 units (in thermal terms) of NG was obtained experimentally during test sintering and was due to an increase in the completeness of coke carbon combustion due to an expansion of the high-temperature combustion zone. In a series of experiments with a sintered layer height of 500 mm, coke consumption was additionally reduced by 10% (rel.) compared to sintering with a layer height of 350 mm.

The components of the sintering charge were dosed according to the results of calculating the charge for experimental sintering under various gaseous fuel supply conditions. When preparing the sintering charge, large fractions of iron ore materials (more than 10 mm) were screened out, reducing the influence of the instability of the granulometric composition of the components on the results of pelletization and the sintering process.

The sinter mixture was mixed, moistened and pelletized · in a drum pelletizer under identical conditions:

– mixing without moistening for 2 min;
– pelletizing with moistening to optimal humidity (7.0–7.5%, characteristic of the charge operating conditions of the Ural Steel Company [20]) for 2 min;
– pelletizing without moistening for 1 min.

To assess the results of pelletization and the identity of the experiments, samples of the pelletized charge were taken, followed by a determination of the moisture content, particle size distribution, and equivalent (harmonic mean) diameter of the granules. The mixture prepared for sintering was loaded into a sinter pot into which a layer of **sinter returns** weighing 2 kg (30–40 mm along the height of the sinter pot) and with a particle size of 5–10 mm was previously laid.

To safely supply gaseous fuel to the layer of sintered charge and maintain the specified parameters for its dosing, the sintering plant was endowed with a cap (Fig. 1) equipped with shut-off and measuring equipment to supply gaseous fuel and air, the forced supply of which at a flow rate 10 times higher than that of gaseous fuel ensures good mixing conditions and prevents the formation of explosive mixtures.

To avoid the ignition of NG above the surface of the sintered charge, the supply of gaseous fuel was started 1 min after ignition, during which water was sprayed onto the sintered charge surface. NG was supplied for 10 min on experimental sintering series Nos. 2–4 and for 15 min at a layer height of 500 mm, which approximately corresponded to 2/3 of the sintering duration and provided an improvement in the temperature-time conditions for the formation of the upper and middle parts of the sinter **cake**.

Fig. 1 Diagram of the sintering plant: *1* sinter pot; *2* grate; *3* vacuum chamber; *4* bed; *5* pressure gauge; *6* thermocouple; *7* valve; *8* collector; *9* dust collector; *10* exhauster with filter; *11* chimney; *12* support system; *13* rotary wheel; *14* flow meter; *15* mixer; and *16* cap
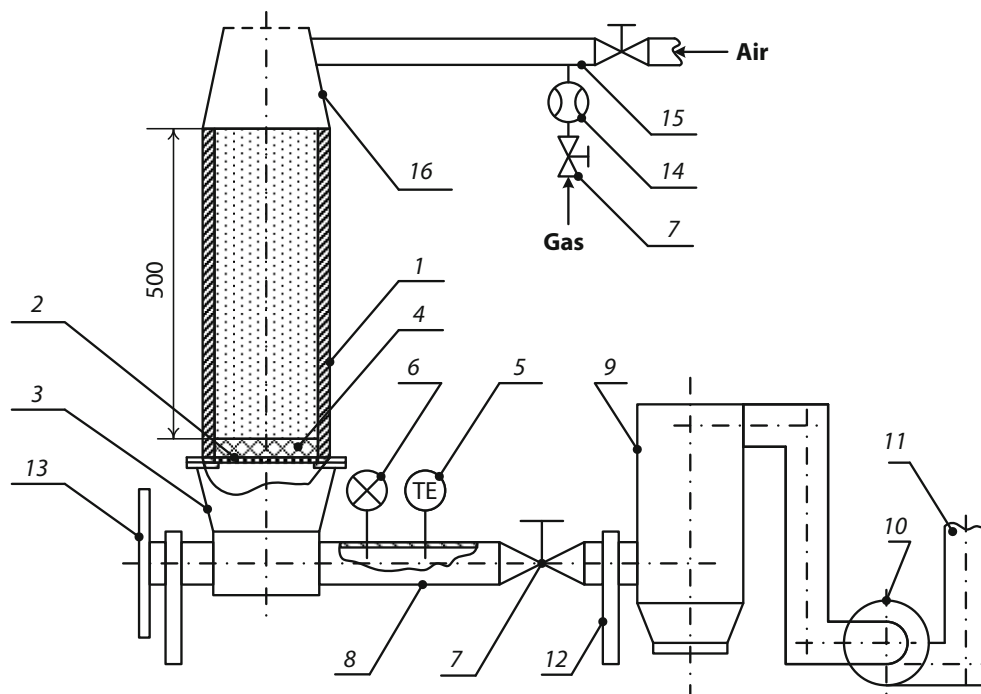
During sintering, the main parameters of the sintering process were recorded, namely, the vacuum in the vacuum chamber (after turning on the vacuum pump, after ignition, and upon completion of sintering), the temperature in the vacuum chamber (maximum value), sintering duration, and shrinkage amount.

Upon completion of the sintering process and cooling of the sinter to 100 °C, the resulting agglomerate was unloaded from the sinter pot, and the sinter was weighed. The resulting sintering mass was subjected to triple dropping (according to GOST 25471-82) with subsequent granulometric composition and yield determination. The yield sinter was subjected to mechanical tests, which involved determining the impact and abrasion strength in a rotating drum according to GOST 15137–77.

To eliminate errors when performing the study, at least three sinterings were performed in each series of experiments to achieve reproducibility of the results. The conditions for conducting the experimental sinterings are summarized in Table 1.

Experiment results

The average results of experiments to study the influence of the consumption of gaseous fuel supplied to the sintered charge layer on the sintering performance and the quality of the sinter are presented in Table 2, 3 and 4.

Data presented in Table 2, 3 and 4 indicate identical experimental conditions, which is confirmed by the stable moisture content of the pelletized charge at the level of 7.15–7.35% in the experimental series of sintering (Table 2), as well as low deviations from the established parameters in basicity and MgO content in the agglomerate (Table 4).

In general, by comparing the average results of laboratory sintering using traditional technology (series 1) and experimental technology with the supply of gaseous fuel to the layer of the sintered mixture (series 2–5), we can conclude that under relatively constant experimental conditions, when NG is fed into the sintered mixture layer, the indicators of the sintering process and the sinter quality exceed similar indicators achieved when using only solid fuel. The efficiency of using gaseous fuel is further increased with the height of the sintered layer.

The improvement in the results of the sintering process with the supply of gaseous fuel into the layer is obviously explained by the improvement in the temperature-time conditions of sintering (the temperature in the

Table 1 Conditions for Experimental Sintering

Indicator	Values for the experimental batches				
	1 (basic)	2	3	4	5
Height of the sintered layer (mm)	350				500
C content in the charge, %	4.2	3.79	3.53	3.26	3.42
NG consumption, m^3/t of sinter	0.0	3.0	5.0	7.0	3.0
Fuel consumption, kg e.f./t of sinter*	53.22	52.57	52.01	51.45	47.73
Consumption of sintering charge components, kg/t of sinter cake					
MMPP ore	157.13	157.36	157.50	157.65	157.73
LebMPP concentrate	715.82	716.85	717.50	718.17	718.57
Limestone	212.92	211.95	211.34	210.71	210.34
BOMD ore	92.57	92.79	92.93	93.07	93.15
Return	250.00	250.00	250.00	250.00	250.00
Coke breeze	57.75	52.30	48.67	45.04	47.07
TOTAL (without return)	1236.19	1231.25	1227.94	1224.64	1226.86

Note. Based on the calorific value of 1 kg of equivalent fuel (or 1 m^3 of gaseous fuel) 29.3 MJ with a calorific value of NG 41 MJ/m^3 and a calorific value of coke breeze 27.1 MJ/kg

Table 2 Average Results of Preparing a Sinter Charge for Sintering

Indicator		Values for the experimental batches				
		1 (basic)	2	3	4	5
Charge moisture content, %		7.35	7.2	7.25	7.15	7.25
Fractional composition of pelletized charge, %	+10 mm	5.10	4.88	3.87	3.25	4.12
	5–10 mm	20.94	22.53	26.89	25.78	27.97
	3–5 mm	30.15	32.16	31.41	35.95	35.16
	1–3 mm	36.85	33.92	31.87	29.59	28.30
	0–1 mm	6.96	6.51	5.97	5.44	4.44
Degree of pelletization of fines fr. 0–1 mm, %		89.51	90.20	91.03	91.83	93.32
Equivalent diameter of pelletized charge granules (mm)		4.19	4.30	4.42	4.40	4.61

Table 3 Controlled and Calculated Sintering Parameters

Indicator		Values for the experimental batches				
		1 (basic)	2	3	4	5
Actual consumption of NG, m^3/t of sinter cake		0.00	3.07	5.03	6.97	3.01
Relative shrinkage of the layer, %		11.4	12.3	12.6	12.9	13.0
Rarefaction in the vacuum chamber, kPa	Before ignition	6.4	6.2	6.1	6.0	7.6
	After ignition	9.6	9.5	9.4	9.4	11.4
	At the end of sintering (at $t_{dis\ max}$)	4.6	5.1	5.3	5.5	8.8
Maximum temperature in the vacuum chamber, °C		380	375	360	355	350
Sintering time, min		18.5	16.1	16.7	16.9	24.0
Sintering speed, mm/min		18.9	21.7	21.0	20.7	20.8
Yield (+5 mm) from the sinter after dropping, %		70.06	74.78	76.49	75.41	80.63
Productivity of the sinter yield (after dropping), t/(m^2 • h)		1.33	1.60	1.53	1.50	1.71

Table 4 Average Data on the Chemical Composition and Quality Indicators of Sinter

| Indicator		Values for the experimental batches				
		1 (basic)	2	3	4	5
Fractional composition of the agglomerate after dropping, %	+40 mm	10.28	15.59	16.44	15.81	18.40
	20–40 mm	15.01	15.95	17.08	14.73	15.38
	10–20 mm	24.45	25.84	27.53	29.33	30.63
	5–10 mm	20.32	17.40	15.44	15.54	16.23
	5–0 mm	29.94	25.22	23.51	24.59	19.37
Tumbler strength, %	Impact	64.75	68.63	70.11	72.11	71.55
	Abrasion	5.63	5.11	5.02	4.78	5.13
Actual composition of the agglomerate, %	Fe total	55.37	55.61	55.72	55.67	55.80
	FeO	11.12	12.61	12.71	12.23	12.84
	SiO_2	7.24	7.4	7.34	7.2	7.3
	CaO	11.5	11.7	11.8	11.6	11.7
	Al_2O_3	0.89	0.81	0.88	0.79	0.84
	MgO	1.67	1.61	1.56	1.63	1.65
	S	0.045	0.037	0.034	0.032	0.034
	P_2O_5	0.041	0.039	0.038	0.041	0.045
Basicity (CaO/SiO_2), un		1.59	1.58	1.61	1.61	1.60
Residual carbon content, %		0.47	0.22	0.11	0.06	0.08

sintered layer and the holding time at temperatures above 1200 °C) [1, 4–6, 15–19]. To evaluate them in two experimental sinterings, a basic one (series No. 1) and an experimental one with NG consumption of $3 m^3/t$ of sinter (series No. 2) at a sintered layer height of 350 mm, temperature measurements were performed at two levels along the sintered layer height of the charge, namely, upper (at a distance of 150 mm from the charge level in the sinter pot) and lower (at a distance of 100 mm from the level of the bed). The temperature dynamics of the sintered charge in the upper and lower levels are presented in Fig. 2.

The data presented in Fig. 2a confirm an improvement in the temperature-time conditions for the formation of agglomerates in the upper part of the layer, which is mainly expressed as a twofold increase in the residence time of the charge in the liquid-phase sintering zone (more than 1200 °C) from 1.9 to 3.8 min. The duration of sintering at a temperature of more than 1200 °C in the lower part of the layer under basic and experimental conditions was comparable (Fig. 2b), although the supply of NG in experimental sintering was stopped **after** 10 min the start of sintering, i.e., when the combustion zone approached the level of the lower thermocouple. Simultaneously, because of the lower consumption of coke breeze in experimental sintering, the temperature of the sintered charge in the lower part of the layer remained in the favorable range of 1200–1400 °C, in contrast to the basic conditions, under which the maximum temperature increased to 1430 °C. In addition, one can note a decrease in the sinter cooling rate when feeding NG into the layer, which also improves the conditions for sinter formation.

The best performance of the sintering process in terms of yield, sintering speed, specific productivity, and sinter quality was achieved under various experimental conditions.

The sintering rate reaches maximum values at an NG consumption of $3 m^3/t$ of sinter (series No. 2) and decreases with a further increase in gas consumption and an increase in layer height. This pattern is due to the simultaneous change in the conditions of pelletization and sintering when using gaseous fuel. In contrast, the use of gaseous fuel, which partially replaces coke breeze, improves pelletizing conditions [1, 16–18, 21], which is manifested in an increase in the proportion of the 5–10 mm fraction while simultaneously reducing the content of granules with particle sizes of 0–1 mm and 1–3 mm (Table 2). In addition, the expansion of the high-temperature combustion zone and an increase in the intensity of heat transfer accelerate the charge heating, contributing to

Fig. 2 Temperature dynamics in the upper (**a**) and lower (**b**) parts of the sintered layer
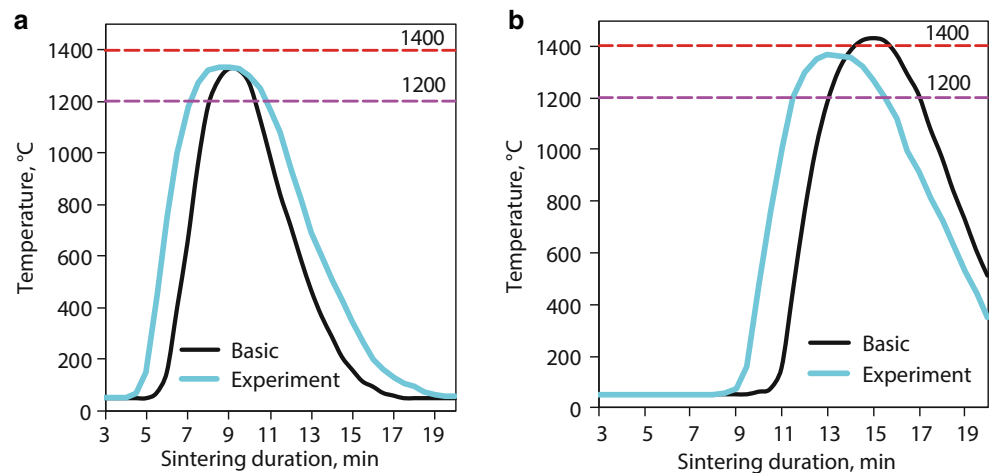
an increase in the sintering rate. However, the expansion of the high-temperature zone promotes more complete melting of the sinter charge, which increases shrinkage, resulting in a decrease in the gas permeability of the sintered layer, which is also confirmed by an increase in rarefaction at the end of sintering (Table 3) Consequently, despite the potential increase in the gas permeability of the raw charge column with increasing gas consumption, which is confirmed by a decrease in rarefaction after ignition (Table 3), the gas permeability during the sintering process decreases, causing a decrease in the sintering rate at increased NG consumption. An increase in the height of the sintered layer leads to an increase in pressure loss, accompanied by additional shrinkage and deterioration of gas permeability. In this case, compared with the basic sintering conditions, the supply of gaseous fuel to the sintered charge layer ensures an increase in the layer gas permeability and the sintering rate not only at a stable height of the sintered charge layer but also when it increases to 500 mm.

Yield and fines content (0–5 mm) in the agglomerate

An improvement in the temperature-time conditions of sintering when gaseous fuel is supplied to the sintered charge layer, manifested in the expansion of the high-temperature zone of liquid-phase sintering (1200–1400 °C) and a decrease in the cooling rate of the agglomerate, increases the yield of usable agglomerate (after dropping) compared with the basic conditions:

– by 6.7–9.1% (rel.) when supplying gaseous fuel and a layer height of 350 mm;
– by 15.1% (rel.) at a layer height of 500 mm and gas consumption of $3 \, m^3/t$ of sinter.

The considerable increase in the yield with increasing sintered layer height to 500 mm (series No. 5) is due to a decrease in the proportion of the upper part of the layer (30–50 mm), which is formed in the period from the moment of ignition to the start of gaseous fuel supply to the layer, i.e., under conditions of heat deficiency due to reduced coke breeze consumption.

A mirror image of the increase in yield in the experimental series with the supply of NG into the sintered charge layer was the reduction in the proportion of fines (0–5 mm) in the sinter after dropping from 29.9% (with the traditional method of fuel supply) to 24.6–25.2% in experimental series Nos. 2–4 (with a layer height of 350 mm) and down to 19.37% with a layer height of 500 mm.

In industrial sintering conditions, with a smaller share of the influence of the "near-wall effect," a further increase in the yield can be expected (as well as a decrease in the fines content) with an increase in the consumption of gaseous fuel supplied to the layer of the sintered charge. However, the underbaking of the upper part of the charge is not eliminated, which is a disadvantage of this method of increasing the efficiency of the sintering process.

Specific productivity

A direct consequence of the observed increase in yield and sintering rate when gaseous fuel is supplied to the layer is an increase in specific productivity, which in the experimental series (Nos. 2–4) at a layer height of 350 mm increased relative to the base level (series No. 1) by 13.2–20.7% (rel.), and with a layer height of 500 mm, the increase in productivity was 28.5% (rel.).

Residual carbon and sulfur content

An expansion of the high-temperature zone of liquid-phase sintering (1200–1400 °C) and, accordingly, an increase in the duration of charge residence in the combustion zone contributes to an increase in the degree of combustion of solid fuel carbon, which is confirmed by a substantial decrease in the content of residual carbon in the agglomerate in experimental sinterings with NG feeding into the layer (Table 4). More complete use of solid fuel in the experimental series enables a reduction of its consumption by an amount exceeding the thermal equivalent of the amount of heat introduced with gas without worsening the thermal conditions of sintering, which is manifested in a decrease in the consumption of equivalent fuel (Table 1). The confirmation of normal thermal sintering conditions in the experimental series is the stable FeO content in the agglomerate at a level of 12.2–12.8%, which exceeds similar values for basic conditions (Table 4). The latter suggests the possibility of further reducing coke breeze consumption without deteriorating the thermal conditions of sintering and the yield and strength properties of the agglomerate.

An additional effect of reducing coke breeze consumption is a decrease in the sulfur content in the agglomerate (from 0.045% to 0.032–0.037%), The removal of this content with the exhaust gases also contributes to an increase in the completeness of solid fuel combustion.

Tumbler strength of the agglomerate

The improvement in the tumbler strength of the agglomerate in the experimental series with NG fed into the layer (Table 4) is due to an increase in heat exchange efficiency with the expansion of the high-temperature combustion zone, as well as more complete combustion of solid fuel, which ultimately ensures the creation of favorable thermal conditions for sinter formation, promoting completion of solid- and liquid-phase sintering processes. The result is an agglomerate with a minimum amount of internal stress with a bonding phases based on calcium ferrites and hematite with a minimum proportion of glassy phases [4–6, 16–18, 22, 23].

Conclusion

The results of experimental sintering enable us to conclude that introducing gaseous fuel into the sintered charge layer provides substantial improvement in the sintering process performance and the quality characteristics of the sinter compared with traditional sintering technology. Increasing the height of the sintered layer with a simultaneous supply of gaseous fuel to the layer is an additional factor in improving the sintering process performance. The results obtained are due to an improvement in the temperature-time conditions of sintering because of the expansion of the high-temperature combustion zone, which contributes to a more complete involvement of the charge ore part in the melt formation processes and ensures a more complete use of solid fuel.

Based on the totality of indicators, the optimal consumption of gaseous fuel supplied to the layer of sintered charge, with an NG consumption of 3 m³/t of sinter (series No. 2 and series No. 5), should be considered the option.

To increase the efficiency of using gaseous fuel in terms of leveling the thermal conditions of sintering along the height of the sintered layer, gas consumption should be smoothly reduced as the combustion zone displaces to the lower levels, i.e., as the sintering carts move along the working part of the sintering machine. This technological method is analogous to the redistribution of solid fuel along the height of the sintered layer, but its implementation is simpler.

When implementing agglomeration technology with the supply of gaseous fuel to the sintered charge layer, some limitations must be considered:

- the possibility of self-ignition of gaseous fuel above the sintered layer, which prevents gas supply within 1 min after ignition, and the gas supply device should be equipped with an automatic shutdown system in case of self-ignition or overheating of the injectors [19];
- the need to use solid fuel with a minimum amount of large fractions (>3 mm), which increases the probability of ignition of gaseous fuel above the layer due to longer combustion;
- deterioration in comparison with the traditional sintering option of the sintering conditions of the upper part of the sinter charge (30–50 mm), formed in the first minute after ignition without a supply of gaseous fuel but with a lack of solid fuel.

The negative consequences of using the technology of supplying gaseous fuel to the sintered layer are reduced by increasing the layer height. In this case, an increase in the sintered layer height must necessarily be accompanied by an increase in the quality of pelletization, in terms of the degree of pelletization of fines, and the strength of the granules.

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