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Improving the Energy Efficiency of Blast Furnaces at PAO NLMK

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Abstract—Analysis of measures used to reduce energy expenditures shows that methods in which a single parameter is changed are ineffective. Coordinated adjustment of several parameters is required. Theoretical analysis reveals the combinations of parameters with the greatest effect. The influence of the granulometric composition of the sinter on the blast-furnace efficiency is considered in terms of the influence of the mean piece size on the reduction rate and the gas dynamics of the upper furnace region. When the reaction $FeO + CO = Fe + CO_2$ reaches equilibrium, the heat consumption in smelting is reduced by increasing the smelting rate. Analysis of specific approaches to reducing the heat consumption in blast furnaces for the example of PAO Novolipetskii Metallurgicheskii Kombinat (NLMK) indicates the basic measures that decrease heat consumption: optimization of the iron ore by reducing the proportion of the >45 mm fraction; increase in output of the blast furnaces to 75–90 t/day (per m^2 of hearth); operation with the highest permissible pressure (in terms of the charging-unit design); increase in hot strength of the coke to 60–62%; pulverized-coal injection at 140 kg/t of hot metal; and optimization of the ore distribution over the furnace radius. Between 2013 and 2016, those measures decreased coke consumption by more than 10 kg/t of hot metal. In addition, the total consumption of carbon fuel was reduced.

Keywords: blast furnace, coke consumption, total carbon consumption, smelting rate, elevated furnace pressure, iron oxides, reduction rate, energy expenditures, heat losses, batch quality, thermal balance

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The energy efficiency of blast furnaces may expediently be assessed in terms of the total carbon consumption per 1 t of hot metal of specified quality that is produced.

The energy and fuel consumption of a blast furnace is lowered by increasing the iron content in the iron ore; more fully utilizing the reducing properties of the gas; boosting the blast temperature; and decreasing the heat losses in the cooling system.

The mean energy consumption per 1 t of hot metal produced is 20 GJ/t for the blast furnaces at PAO Novolipetskii Metallurgicheskii Kombinat (NLMK). For some blast furnaces, the figure is 15 GJ/t [1].

In the best blast furnaces operating with well-prepared iron ore and with coke of hot strength $CSR > 65\%$, the efficiency of the reducing process is close to the thermodynamic limit [2].

Analysis of measures used to reduce energy expenditures shows that methods in which a single parameter is changed are ineffective. Coordinated adjustment of several parameters is required [3, 4].

One means of decreasing the heat consumption is to minimize the heat losses. Fluctuations in the heat expenditures in the lower zone of the blast furnace (Q_{low}) and the heat losses (Q_{lo}) are largely determined by fluctuations of the heat consumption in the direct reduction of iron oxides (Fig. 1), as follows from analysis of the heat balance by the method in [5].

The relation between the heat losses and the heat consumed in direct reduction of FeO permits the following account of the factors that affect the heat losses. With change in quality of the iron ore and/or the ore distribution over the furnace radius, the degree of indirect and hence direct reduction of the iron oxides changes. The production staff eliminates the heat deficit or excess by adjusting the heat input to the lower zone of the blast furnace. This is accompanied by change in heat transfer in both lower and upper zones of the furnace. Any fluctua-

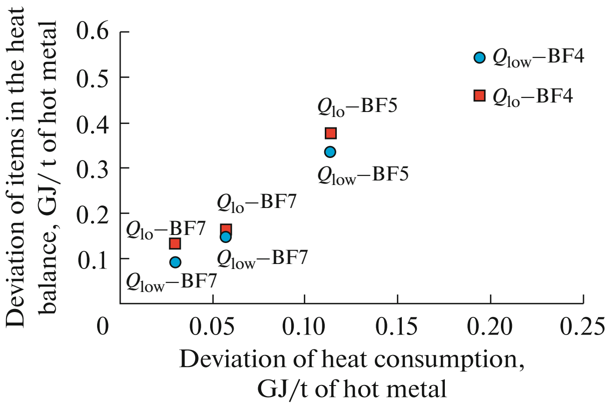

Fig. 1. Relation between the fluctuations in the heat balance and in heat consumption (mean square deviations) during the direct reduction of FeO (2014 data): BF, blast furnace.

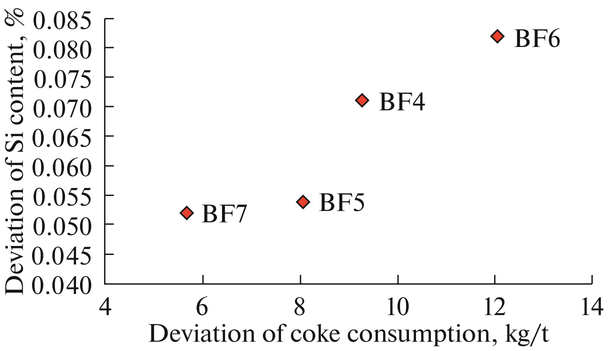

Fig. 2. Relation between the fluctuations in the hot metal's silicon content and in heat consumption (mean square deviations) during the direct reduction of FeO (2014 data). The heat consumption is expressed in terms of the coke consumption.

tions in the heat losses will affect the composition of the products (Fig. 2).

These results show that one approach to boosting the energy efficiency of the blast furnace is to stabilize the indirect reduction of iron oxides, which largely depends on the degree of utilization of carbon monoxide.

The residence time of the batch in the furnace with change in the degree of CO utilization may be described as follows, within the framework of the model in [6–8]

$$\Delta\eta_{CO} = \frac{\eta_{CO}^{eq}}{\eta_{CO}} \frac{ke^{k\tau}}{e^{k\tau} - 1} \Delta\tau.$$

Here the factor k takes account of the influence of the reaction rate constant; η_{CO}^{eq}, η_{CO} are the equilibrium and actual degrees of CO utilization in the reaction $FeO + CO = Fe + CO_2$; τ is the residence time of the batch in the indirect-reduction zone; $\Delta\tau$ is its increment. According to operational data for blast furnaces, k is between –0.48 and –0.56.

On the basis of that equation, we see that the residence time of the batch in the furnace has less effect on indirect reduction as the reaction $FeO + CO = Fe + CO_2$ approaches equilibrium. The influence of the batch's residence time on the indirect reduction also declines with increase in the reaction rate, which depends on the temperature and the piece size [9, 10].

By simultaneous solution of the equations describing the bed's gas dynamics and the rate of reduction, we find that furnace performance is best when the content of the 5–25 mm fraction is at least 80%. The content of the fraction smaller than 5 mm and larger than 45 mm must be no more than 5%. Analogous results may be found in [11].

The residence time of the iron ore in the blast furnace may be increased if the coke is replaced by pulverized coal [12, 13]. Increase in the ore load during pulverized-coal injection shrinks the furnace volume occupied by coke. Hence, without change in the smelting rate, the residence time of the iron ore in the zone of indirect reduction is increased. With the introduction of pulverized-coal injection, the degree of CO utilization in the blast furnace at PAO NLMK rises by 1.0–1.5%.

If we compare the performance of blast furnaces operating with pulverized-coal and natural-gas injection (furnaces 4 and 5) and blast furnaces without pulverized-coal injection, we find that the total carbon consumption is less in the furnaces with pulverized-coal injection, while the degree of CO utilization is higher (Table 1).

With increase in the smelting intensity, the residence time of the batch in the zone of indirect reduction declines. However, this is accompanied by decrease in the heat losses, as noted by Gotlib [14]. Without change in the batch conditions, the heat

Table 1. Furnace operation with and without pulverized-coal injection

Blast furnace	Daily output, t	Total carbon consumption, kg/t	Degree of CO utilization, %
Furnace 3	5040.2	429.6	46.4
Furnace 4	5803.9	409.3	49.9
Furnace 5	8093.9	413.4	50.1
Furnace 6	8810.5	415.1	48.9
Furnace 7	12220.0	398.2	49.2

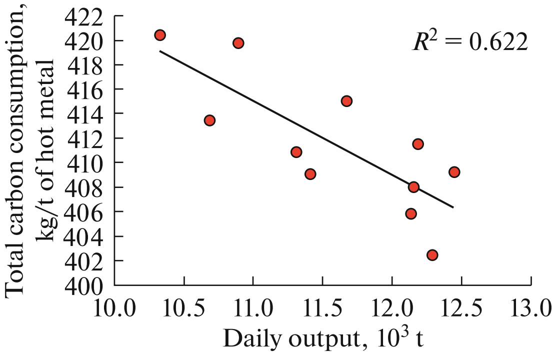

Fig. 3. Relation between the total carbon consumption and the daily blast-furnace output.

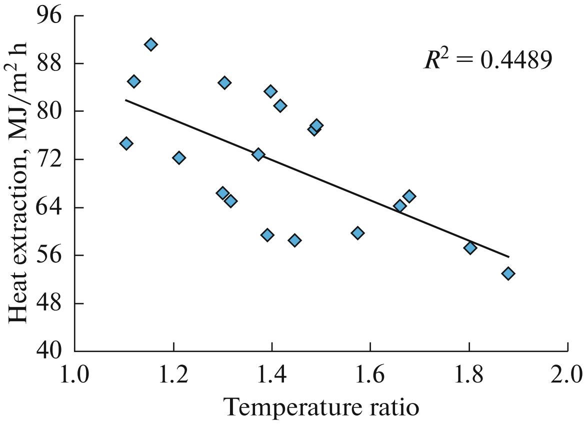

Fig. 4. Relation between the heat extraction from the shoulders and the ratio of the peripheral and mean temperatures of the furnace gas.

losses in the blast furnace are inversely proportional to the productivity, according to the data in [14]. This is confirmed by analysis of the relation between the mean total carbon consumption and the daily output of the Rossiyanka blast furnace, according to ten-day averages of data collected from January to April 2016 (Fig. 3).

We find that increase in smelting intensity is an effective means of reducing the energy consumption in the blast furnace.

If the pressure above the batch is increased, with simultaneous increase in coke quality, the smelting intensity may be increased, while the heat losses are decreased [15, 16]. For analysis of the conditions ensuring efficient furnace operation and comparison of furnace performance with different pressure above the batch (Table 2), see [15]. Figures for furnace operation between 2012 and 2014 are compared, with variation in the pressure above the batch by ±10 kPa with respect to the mean.

Analysis shows that hot strength and high quality of the sinter at each blast furnace is required for efficient blast-furnace operation at pressures close to the engineering limit. In fact, with change in pressure above the batch, the upper pressure difference changes less than the lower pressure difference.

In practice, the scope for increasing the lower pressure difference depends on the size of the coke pieces in the batch, the quantity of primary slag and its properties, the quantity of CO formed in the reduction of iron from the primary slag, and the extent of the cohesion zone. For the blast furnaces at PAO NLMK, the mean diameter of the coke pieces must be increased by 3.6% in order to maintain the lower pressure difference. Correspondingly, the degree of indirect reduction increases by 1.4%, while the viscoplastic zone shrinks by 2.3%.

The energy efficiency of the blast furnace also depends on the ore distribution over the furnace radius. Blast furnaces with a nonconical charging system operate with a bulge in the distribution at the furnace axis. Equalization of the ore load in the intermediate and peripheral zones of the furnace will improve the degree of CO utilization. The thermal load on the cooling systems in the shoulders and bosh also increases here.

The nonuniformity of the distribution may be assessed in terms of the ratio of the temperature of the peripheral gases and the mean temperature of the furnace gas, on the basis of the principles developed by the Ural school of metallurgists [17–20]. In Fig. 4, we show the relation between the thermal loads on the cooling systems and the heat extraction from the shoulders.

This dependence is confirmed by the influence of the ore load and the diameter of the iron-ore pieces on the height of the upper heat-transfer section, according to mathematical modeling.

Table 2. Furnace performance with different pressures above the batch

Characteristic	Pressure above the batch, kPa					
	furnace 4		furnace 6		Rossiyanka furnace	
	150	170	154	196	168	230
Total carbon consumption, kg/t of hot metal	413.7	386.7	408.7	400.2	433.1	398.2
Output, t/m^2 day	61.63	74.11	68.42	77.27	65.59	90.7
CSR, %	52	63	49	61	52	66.8

The best ore distribution over the furnace radius is determined by optimization: specifically, the goal is to ensure maximum CO utilization with permissible loads on the cooling systems. To that end, the loading program is changed if the permissible thermal loads on the blast furnace's cooling units are exceeded.

With increase in the smelting intensity, the hot strength of the coke, and the pressure above the batch, the total carbon consumption in the blast furnaces at PAO NLMK was 426.3 kg/t of hot metal in 2014 and 423.2 kg/t of hot metal in 2015.

The total fuel consumption (coke + natural gas + pulverized coal) in the blast furnaces at PAO NLMK is among the lowest in Russia [21].

CONCLUSIONS

The basic measures that increase the energy efficiency of the blast furnaces at PAO NLMK are as follows.

—optimization of the iron ore;

—increase in output of the blast furnaces;

—operation at the highest permissible pressure;

—increase in hot strength of the coke;

—pulverized-coal injection;

—optimization of the ore distribution over the furnace radius.

Between 2013 and 2016, those measures decreased the coke consumption of the blast furnaces at PAO NLMK by more than 10 kg/t of hot metal.

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