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EFFECT OF THE FUEL, RAW MATERIALS, AND PROCESS CONDITIONS ON THE BEHAVIOR OF TEMPERATURE CHANGE IN A BLAST-FURNACE LINING

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Results are presented from an analysis of the temperature of the lining in the shaft and bosh of a blast furnace over a 2.5-year campaign. It is shown that changes in the temperature of the lining over the height and about the circumference of the furnace are affected by changes in the parameters of the raw materials and the smelting process. For example, lining temperature is affected by changes in the charging program, the amount of manganese-bearing materials in the charge, the number of closed tuyeres and their locations, the quality of the charge materials, the chemical and component-by-component composition of the iron-ore-bearing part of the charge, and the distribution of the components of the charge across the furnace.

Keywords: *blast furnace, lining, temperature of blast-furnace lining, charge materials, charging regime, blast-furnace smelting technology.*

Blast furnace No. 3 (BF-3) at the Enakievo Metallurgical Plant (EMZ), returned to operation in 2011 after an overhaul [1, 2], is equipped with thermocouples installed in the lining of the shaft over the height of the furnace and about its circumference. The thermocouples are installed at seven levels in the shaft and the upper and lower part of the bosh of BF-3, eight levels over the height of the hearth, and four levels in the central cylinder of the bottom. Thermocouples are installed as follows about the furnace's circumference: eight thermocouples at the bosh level and the three lowest levels in the shaft, six thermocouples in the next two highest levels in the shaft, and four thermocouples at the highest level in the shaft.

To analyze the nonuniformity of the shaft lining's temperature and the corresponding nonuniformity of the distribution of gas-flow temperature about the furnace circumference, the data obtained from the thermocouples at nine levels in the shaft were divided up into sectors from the tuyere zone to the top of the furnace and averaged over the furnace's height. Each of these 60° sectors was chosen in accordance with the operating regime of the chute of the BCA (bell-less charging apparatus) about the furnace circumference.

With allowance for features of the processes which take place during blast-furnace smelting, the structure of the stock (including the dry zone at the upper levels of the shaft) and the zone in which the charge materials are in the viscoplastic state, in order to analyze the temperature of the lining we conditionally divided the shaft of BF-3 into two sections: the bottom part of the shaft and the upper part of the bosh constitute the region which is nominally below the viscoplastic zone; the top part of the shaft is the region which is nominally above the viscoplastic zone.

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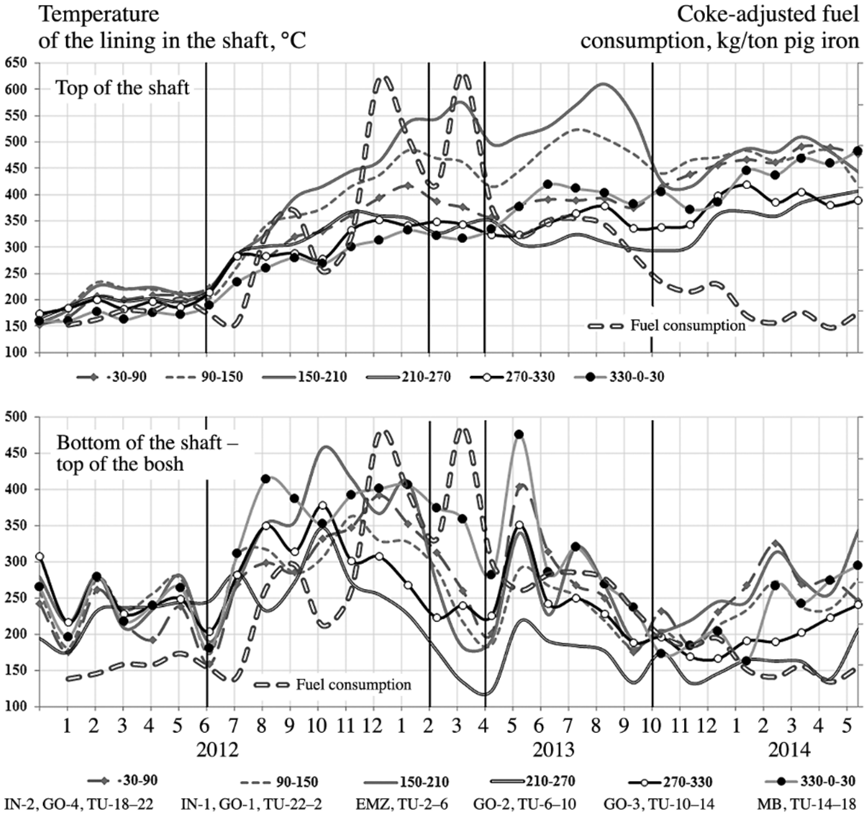

Fig. 1. Change in the temperature of the lining of BF-3 about its circumference from the beginning of the campaign.

Figure 1 shows the change in the average monthly temperatures of the shaft lining in BF-3 about the circumference of the furnace. The data on the temperature variation are shown for the period from the beginning of the lining's campaign and were analyzed in accordance with an algorithm that was developed. The six sectors in the furnace for which the temperatures are shown correspond to the garage positions of the BCA chute and are oriented as follows in relation to the equipment of BF-3:

- the 30–90° sector – iron notch IN-2, gas offtake GO-4, and tuyeres TU-18–22;
- the 90–150° sector – IN-1, GO-1, and TU-22–2;
- the 150–210° sector – the electromechanical probe (EMP) and TU-2–6;
- the 210–270° sector – GO-2 and TU-6–10;
- the 270°–330° sector – GO-3 and TU 10–14;
- the 330°–0°–30° sector – the access hole of the BCS (AH) and TU-14–18.

It follows from the results which were obtained (see Fig. 1) that the temperature of the lining varied within 150–250°C in the top part of the shaft and within the range 150–300°C in the bottom part of the shaft during the initial months of the campaign of BF-3 (from December 2011 to June 2012), when the furnace was operating on coke of the Premium class (Table 1) and sinter purchased from the Southern Mining-Concentration Combine and Mariupol Metallurgical Combine. From July 2012, when there was a changeover to high-basicity (1.81–2.22 units) locally produced sinter and coke of lower quality (Table 1), temperature increased gradually to 400°C in the top part and jumped sharply to 400–450°C in the lower part. These changes were accompanied by an increase in the range of variation of temperature about the furnace circumference in both the upper and the lower zones.

The temperature of the shaft lining (in the top and bottom parts) began to decrease in February 2013 after BF-3 was changed over to the charging program in [3] due to rapid burning of the tuyeres, forced operation of the furnace with light rounds,

TABLE 1. Characteristics of the Coke Used on BF-3 in 2012

Characteristic	Coke of the Premium class (January–June 2012)		Standard coke (July–December 2012)		
Content of the classes of coke, %	58	42	10	74	16
CSR/*CRI*	55/28	46/35	52/33	43/39	38/42
Note: Indices of coke quality: *CSR* – hot strength; *CRI* – reactivity.					

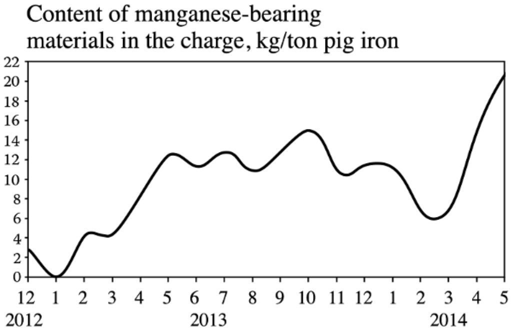

Fig. 2. Changes in the average monthly content of manganese-bearing raw materials in BF-3.

and the need to use of manganese-bearing materials to wash out the hearth. The temperature of the lower part of the shaft and the upper and lower parts of the bosh decreased from the value of 342°C recorded during the period December 2002 – January 2003 to 201°C in April 2013. Temperature in the top part of the shaft during the test period decreased from 400 to 376°C.

To prolong the service life of the BCA chute, the length of its ribbed-honeycomb lining was gradually increased from April to October 2013. Its length was decreased by 38% in April and by 65% in October compared to the length of the lining of the chute installed on BF-3 in 2011 after the overhaul. A change in the ratio of the smooth part of the lining to its ribbed-honeycomb part increased the coefficient of friction of materials in the chute, which made it necessary to change the angles at which the chute is inclined so that the center of the flow of charge materials falls into an annular zone in the top of the furnace. With allowance for the above, new angles for the inclination of the chute were calculated and introduced on BF-3 at the beginning of October. To check the correctness of these angles, during the next furnace shutdown specialists from the Institute of Ferrous Metallurgy conducted studies in which the method in [1] was used to determine the characteristics of the flow of charge materials during the charging operation. It should be mentioned that the angles of inclination of the chute were not corrected after the first change was made in the ratio of the lengths of the smooth and ribbed-honeycomb parts of the chute's lining in April 2013. The lack of correction became evident from the fact that temperatures increased in both the upper and the lower parts of the shaft (see Fig. 1).

The introduction of new angles for the chute's inclination in October 2013 and the use of an improved method for shifting the pairs of points where rounds are charged about the circumference of the furnace narrowed the range of variation of temperature in the top part of the shaft around the furnace (Fig. 1). The rms deviation of temperature was 51°C from October 2013 to May 2014, compared to the 79°C in the previous period (April – September 2013). The changes in temperature in the top and bottom of the shaft correlate quite well with the coke-based equivalent of fuel consumption (Figs. 1 and 3). The correlation coefficient for the rms deviation of lining temperature about the circumference was 0.63 in the top part and 0.59 in the bottom part.

The range of variation of the temperatures in the bottom part of the shaft and the top and bottom parts of the bosh increased about the circumference of the furnace from November 2013 to March 2014. The expansion of this range was due to a decrease in the quantity of manganese-bearing materials used to wash the hearth from 15 to 6 kg/ton pig iron (Figs. 2 and 3).

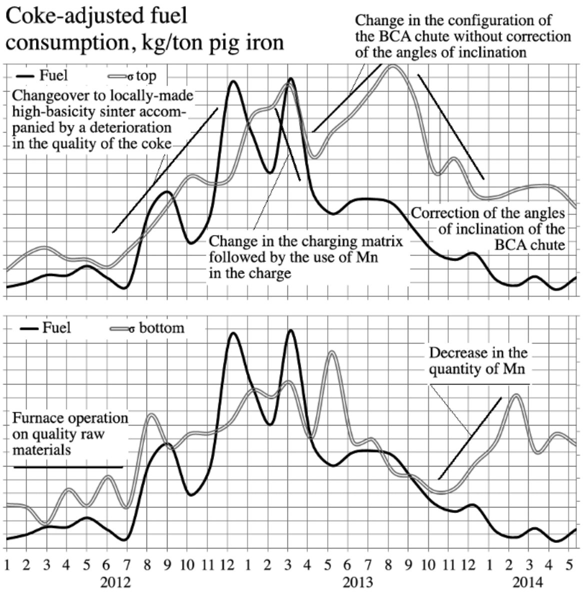

Fig. 3. Change in the coke-adjusted value for fuel consumption and the rms deviation of the temperature of the shaft lining of BF-3 about the circumference of the furnace.

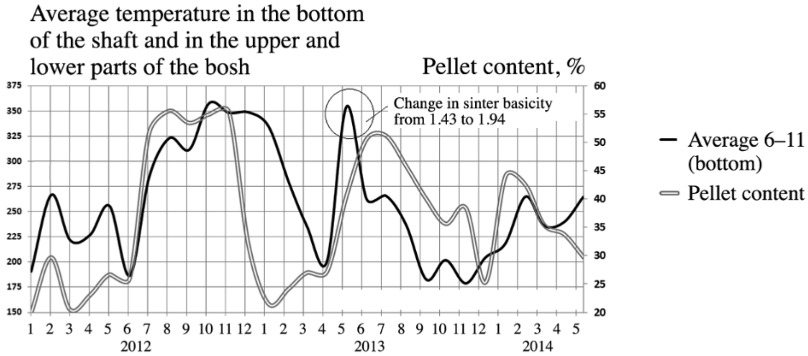

Fig. 4. Change in the temperature of the lining in the bottom of the shaft and the top and bottom parts of the bosh for different pellets contents in the charge.

An analysis of the changes in the absolute values of lining temperature in the bottom part of the furnace showed the existence of a correlation between these temperatures and the pellet content of the charge (Fig. 4). Moreover, since this parameter varied quite broadly (by 20–55%) on BF-3, the temperature of the lining in the bottom part of the furnace also varied from 175 to 360°C. The correlation just mentioned is mainly related to the effect of the pellet content of the charge on the formation of a stable slag crust, which allows the components of the charge to be placed in the skips in the prescribed sequence. When an efficient sequence is chosen, the regime of variation of the concentration of pellets in the wall region of the top of the furnace is 3–4% – which is appropriate for the formation of a stable slag crust. The concentration of pellets can vary more broadly in the pellet-sinter mixture as a whole. The absolute value required for pellet concentration in the wall region of the furnace is determined by the requirements for the primary slags, the quality of the sinter and the pellets, and the proportions of these two materials.

To delimit the factors that cause the technology which is used to affect the temperature of the lining of the shaft and to account for the lining's wear during service, we analyzed its temperature in the shaft of BF-3 for five periods of furnace operation since the beginning of the campaign: first period – 11.24.2011–06.30.2012; second period – 07.01.2012–12.31.2012;

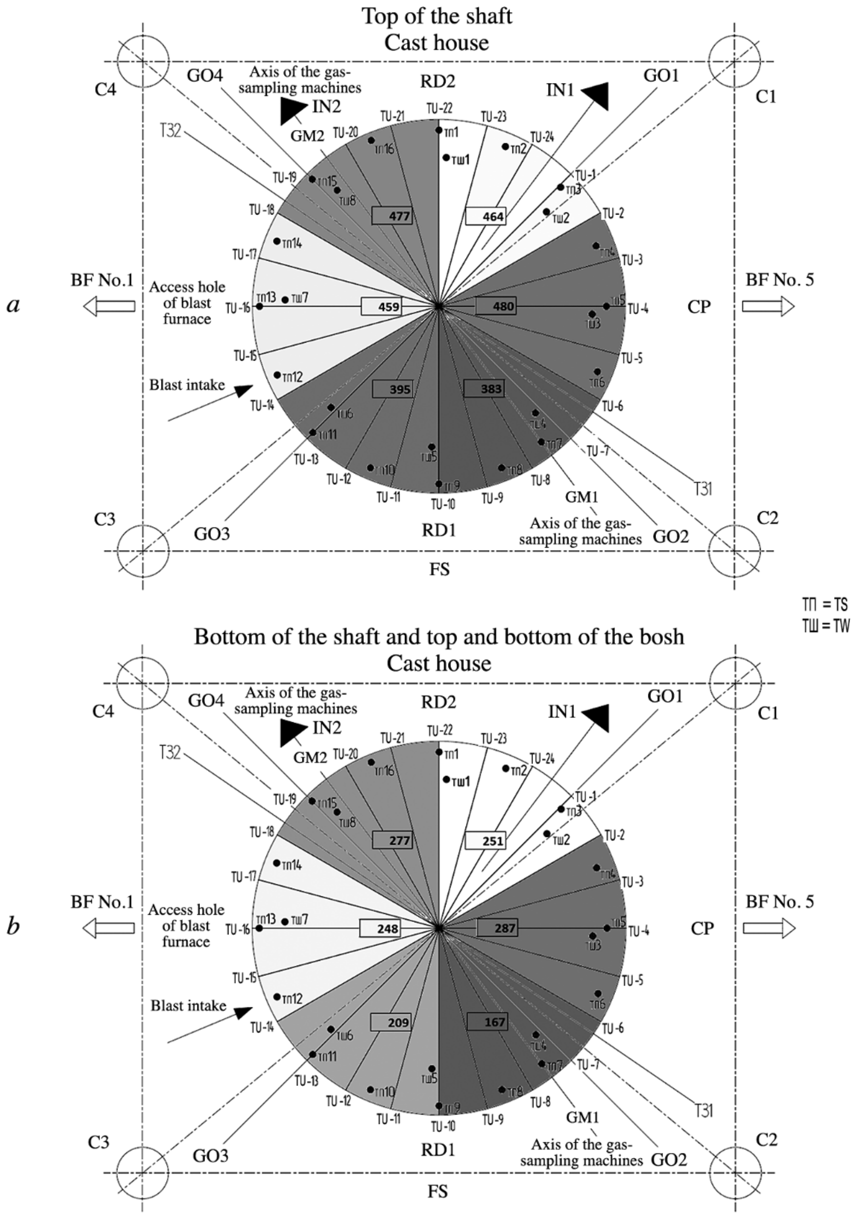

Fig. 5. Distribution of the temperature of the lining of BF-3 for the fifth trial period of operation of the furnace (01.01.2014–05.31.2014): *a*) top of the shaft; *b*) bottom of the shaft and the top and bottom parts of the bosh.

third period – 01.01.2013–06.30.2013; fourth period – 07.01.2013–12.31.2013; fifth period – 01.01.2014–05.31.2014. The temperatures of the shaft were grouped based on changes that took place in such process parameters as the consumption of cold blast, the temperature of the hot blast, the consumption of natural gas, gas temperature at the periphery of the furnace, and the ratio of that temperature to the temperature in the top of the furnace. The process parameters were divided into three ranges of variation before the analysis was begun.

The results of the study established that the character of the change in temperature in the bottom part of the shaft and the top and bottom parts of the bosh is most affected by the temperature of the hot blast. During the five periods that were investigated, a change in the temperature of the blast increased the average temperature of the lining and the nonuniformity of the temperature distribution about the circumference of the furnace. These developments show that a change in blast temperature was accompanied by a change in the position of the zone in which the iron-ore part (IOP) of the charge was in the viscoplastic state. During the first period, when BF-3 was being operated with the use of large amounts of natural gas, an increase in natural-gas use to 6900 m^3/h lowered the temperature in the top part of the shaft and evened out temperature about the circumference of the furnace (compared to the results obtained with 4800 and 5000 m^3/h for the consumption of natural gas).

A diagram showing the distribution of the average temperature in six sectors of the furnace during the five test periods was constructed (see Fig. 5 for the distribution for the fifth period) to analyze how the distribution of the temperature of the lining about the circumference of BF-3 is affected by certain design features of the furnace – particularly the design of the equipment that supplies the blast and the location of the iron notches. The study results showed that in all of the periods the sector of the *top part of the shaft* that was heated the most was located on the side opposite the blast intake: this was sector TU-22–6 in the first period and sector TU-2–6 in the other periods. The sectors that were the most heated were located on the same side as the blast intake (TU-14–18) in the first and second periods and were in the sector containing GO-2 and TU-6–10 in the third, fourth, and fifth periods.

The temperature in the *lower part of the shaft and the upper and lower parts of the bosh* is characterized by the following features. The most heated sector of the furnace was located on the same side as the blast intake: sector TU-10–14 in the first period and sector TU-14–18 in the second and third periods. In the fourth and fifth periods, the most heated sector was located opposite the blast intake – sector TU-2–6 (see Fig. 5*b*). The least heated sector was located on the side that includes IL-2 and TU-18–22 in the first period and on the side that includes GO-2 and TU-6–10 in the remaining periods.

The nonuniformity of the temperature of the lining of blast furnace No. 3 over its entire height can be attributed to changes in the smelting conditions over the 2.5 years of the campaign – changes in the charging program, the amounts of Mn-bearing materials used in the charge, the number of closed tuyeres and their locations, the quality of the charge materials, the chemical composition and component make-up of the iron-ore-bearing part of the charge, and the distributions of the components over different cross sections of the furnace. The nonuniformity of lining temperature along the furnace also attests to changes which occurred in the direction of the gas flow in the stock in the radial and circumferential directions when there were significant variations in the resistance of the stock during smelting. The information which was obtained might be used in the future to substantiate the choices made for the diameter of the tuyeres, the number of closed tuyeres, and those tuyeres' locations and to correct the regime that dictates the circumferential distribution of the charge materials. If natural gas is used (or if a nonuniform distribution of PCF (pulverized-coal fuel) may be formed about the circumference of the furnace), the same information might also be used to control the circumferential distribution of fuel additives which are injected into the furnace.

The temperature distributions about the circumference of the furnace and over its height from the tuyeres to the protective top panels are affected mainly by the transverse distributions of the hearth gases and shaft gases over the furnace height and the quantity, composition, and heat capacity of those gases. The nonuniform radial and circumferential distributions of coke and the iron-ore-bearing part of the charge that are created in the top of the furnace allow more control over the distribution of the gas flow across the furnace and help determine the form of the viscoplastic zone (the zone in which the IOP melts and begins to flow). The implementation of certain measures and variation of the methods used to charge the furnace make it possible to respond in real time to nonuniformity of the gas-flow distribution about the circumference of the furnace and to make that distribution more efficient for the conditions which characterize the radial nonuniformity [4]. The position of the viscoplastic zone over the height of the furnace is determined mainly by the heat-energy parameters of the blast (its temperature and oxygen content and the quantity and composition of the additions to the blast) and the gasdynamic parameters (the amount of blast air and its distribution among the individual tuyeres, wind rate, the composition of the hearth gases, and the relative location and geometric characteristics of the oxidizing zones). These parameters are closely linked to one another through the theoretical combustion temperature and the kinetic energy of the blast when it exits the tuyeres. The same parameters are also significantly affected by the quality of the charge materials (especially the coke) and the composition and radial distribution of the IOP.

Using a charge with an IOP that contains hematite ores and acidic pellets and increasing the volumetric content of these two materials in the charge when they begin to be reduced at the upper levels of the shaft (the dry zone of the furnace) will lead to serious distortion of the layered structure of the stock that is formed in the top of the furnace and thus reduce gas

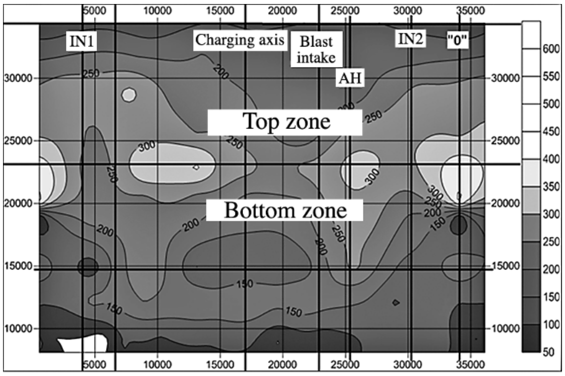

Fig. 6. Thermogram of the readings of embedded thermocouples in BF-3 for the January–June 2012 period following blow-in of the furnace. The furnace was operating on quality charge materials during the period just indicated.

permeability in this zone. The fact that the primary slags formed by these low-melting materials are highly chemically aggressive makes it necessary to distribute them in an intermediate region over the radius of the furnace. Having to distribute them in this manner adversely affects gas permeability in that region and creates conditions which facilitate the flow of substantial volumes of the reducing gases into a narrow constricted zone at the periphery of the furnace. Such a development in turn negatively affects the durability of the lining of the shaft and the performance of the furnace, especially when the angles of inclination of the shaft are low (83°42’44” for blast furnace No. 3 at the EMZ). A reduction in the quality of the materials in the IOP of the charge also negatively impacts the gas permeability of the intermediate region at the upper levels of the shaft and intensifies the peripheral flow of gases. Increasing the content of the finely dispersed component of a charge which already has a high content of ferrous oxide adversely affects the high-temperature characteristics of the coke. The deterioration in coke quality and the increase in the quantity of fine particles of ferrous oxide significantly decrease the gasdynamic characteristics in the tuyere zone and stimulate peripheral gas flow.

Figures 6–9 show isotherms in a cross section of BF-3. The isotherms were constructed based on readings from thermocouples embedded in the shaft, the upper and lower part of the bosh, and the tuyere region. The length of the development is equal to the maximum diameter of the furnace in the upper part of the bosh – 10670 mm. The datum point on the x-axis corresponds to the axis of the cast house (between the notches), while the y-axis extends from a height of 8103 mm to a height of 34400 mm. The heights of different elements of the furnace (mm): lower part of the bosh 14200–17200; upper part of the bosh 17200–19500; shaft 19500–35400 (the bottom of the protective panels in the top of the furnace). The thermocouples embedded in the lining at the same depth relative to its inside surface were located at the following elevations, mm: 14930, 18950, 20120, 22870, 25878, 28878, 31740, 34400. The distance from the internal working surface of the lining to the end of the series of embedded thermocouples was 260 mm. The properties of the lining of the given furnace elements were comparable at the different elevations just indicated.

Element of the blast furnace about its circumference	Number of tuyere	Length of the development, mm
Cast-house axis 0	22	0.0
Iron notch No. 1	24–01	3491.7
Side opposite the blast intake	02–03	6285.1
Charging axis	10	16760.4
Blast intake	14–15	23045.5
Access hole	16	25140.6
Iron notch No. 2	19–20	30029.0
Cast-house axis 0	22	33520.8

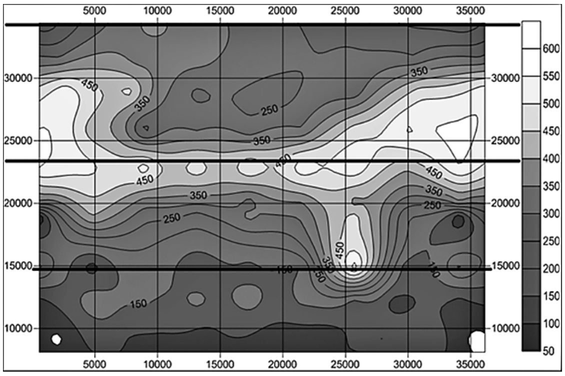

Fig. 7. Thermogram of the readings of embedded thermocouples in BF-3 with the furnace operating at moderate speed on a combination blast with charge materials of satisfactory quality. The operating period was July–December 2012.

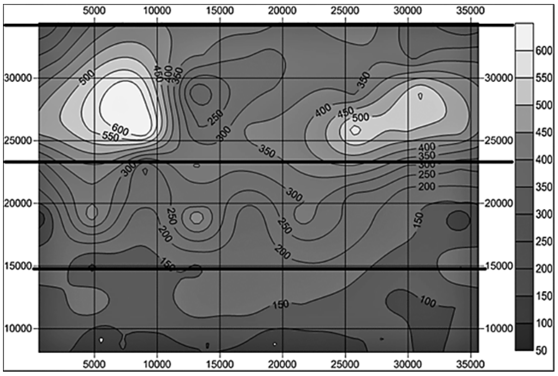

Fig. 8. Thermogram of the readings of embedded thermocouples in BF-3 with the furnace operating at moderate speed on a combination blast with charge materials of satisfactory quality. The operating period was January–October 2013.

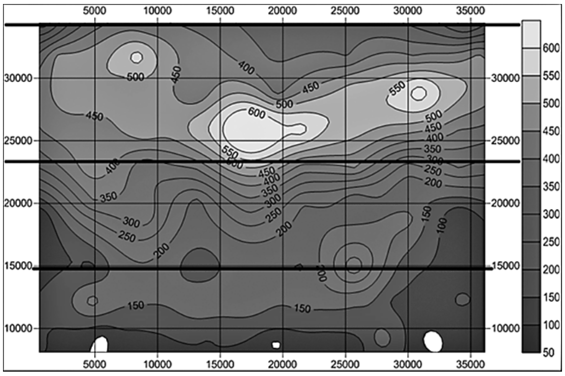

Fig. 9. Thermogram of the readings of embedded thermocouples in BF-3 with the furnace operating at moderate speed on a combination blast with charge materials of satisfactory quality. The operating period was January–June 2014.

As was noted above, the furnace was operated under priority charging conditions in the first test period (01.01.2012–06.01.2012) after its blow-in in the middle of October 2011. It can be seen from Fig. 6 that the most heated side of the furnace (referring to the temperature of the lining) was around and between the iron notches. Such a circumferential temperature distribution is typical of all small and moderate-size blast furnaces on which the iron notches are located on one side of the furnace. The sectors containing the iron notches are characterized by the most rapid descent of the charge materials, particularly during the tapping of the smelting products. The zone having the highest temperatures over the height of the furnace corresponds to the 22870-mm level, with this zone tending to shift downward along the furnace. The overall temperature level is consistent with the condition that the furnace is usually in after a blow-in period.

The levels where the temperature of the lining was highest became more distinct during the second half of 2012 and were at or below the 22870-mm elevation (Fig. 7). The hottest zone over the furnace height on the iron-notch side was within the range 22870–25878 mm. Such a heightwise temperature distribution in a blast furnace is typical of high-rate smelting and indicates that the working surface of the shaft is in good condition. When the furnace is operated on a combination blast and good-quality charge materials that make it possible to maintain the normal smelting rate, the root of the viscoplastic zone should shift as close as possible to the upper part of the bosh. If the charge materials are efficiently distributed over the radius of the furnace, then the temperature distribution just described will correspond to a central gas distribution and the formation of a viscoplastic zone in the form of an inverted V. A central gas distribution and a V-shaped viscoplastic zone maximize the gas permeability of the materials over the height of the furnace and the smelting rate. In the case of BF-3, the V-shaped viscoplastic zone should have corresponded to the elevation range 18950–20120 mm. Such a situation was not realized, however, due to changes in the charging conditions (deterioration of the quality of the coke, an increase in the pellet content of the IOP, and an corresponding increase in the basicity of the locally produced sinter), fluctuations in the gas-energy parameters of the blast, uncorrected problems with the angles of inclination of the distributing chute (these problems were detected later in the automated process control system), and design flaws of the chute.

A further deterioration in the charging conditions and declines in the heat and energy parameters of the blast (down to a level close to operation of the furnace on a blast composed almost entirely of atmospheric air) substantially altered the temperature fields over the height of the furnace. The high-temperature zone was shifted to the 28878-mm level due to a decrease in the oxygen content of the blast and a corresponding increase in the effect of the blast's sensible heat. Those changes led to an increase in the length of the high-temperature zone over the furnace height and its shift toward the upper part of the shaft. In the circumferential direction of the furnace, the hottest zone corresponded to the iron-notch region and was shifted toward the access hole. This shifting was observed throughout the period of operation of BF-3. The increase in temperature in this zone over the entire height of the furnace was due to several factors. First of all, a thermocouple beam had been installed in this zone prior to June 2014 to measure the temperatures above the stockline. However, the beam made the charge-materials distribution in the top of the furnace quite nonuniform because of its design, which resulted in the incoming flow of materials being scattered over that part of the furnace. Secondly, an analysis made of a large volume of data on the operation of the BCA as part of a larger analysis of the factors that could be contributing to the nonuniform charge distribution showed that at the beginning of the charging operation it was impossible to place the chute close to its base position with respect to the circumference of the furnace (that position coincides with the access hole).

As was noted above, it turned out to eventually be possible to alleviate the nonuniformity of the lining's temperature in the circumferential direction within different sectors of the furnace by changing the charging program and charging scheme in accordance with changes in the charging conditions of BF-3 [1–3], correcting the angles of inclination of the distributing chute after making changes to its design, shifting the angles at which materials are charged by 30° about the furnace's circumference, and making substantiated choices for the diameter, locations, and number of closed tuyeres (Figs. 1, 6, and 8).

The operation of BF-3 was characterized by low gasdynamic stability due to the continued deterioration in the quality of the charge materials, an increase in the pellet content of the IOP, a decrease in the oxygen content of the blast and the frequency with which oxygen was used in the blast, and a decrease in natural-gas consumption brought about by design-related factors. Increasing the temperature of the hot blast to compensate for the decrease in theoretical combustion temperature caused by the reduced oxygen content of the blast led to an increase in the physical-heat component of the blast and the hearth gases. In aggregate, these factors increased the dynamic viscosity of the hearth gases, increased the resistance to their passage through the coke column, and thus reduced gas flow rate in the furnace as a whole while intensifying the peripheral gas flow. The increase in the nitrogen content in the tuyere gases when the furnace was operated on a blast that was close in composition to atmospheric air led to an increase in the height of the high-temperature zone over the height of the furnace and shifting of this zone to higher levels in the shaft.

During recent periods of operation of BF-3 (see Fig. 8) and before it was shut down for guniting in June 2014 (Fig. 9), there was a steady decrease in the nonuniformity of the temperature distribution about the circumference and along the height of the furnace and a reduction in the temperature of the lining on the side of the furnace where blast air is supplied to the bustle pipe – in the area of iron notch No. 2. This development was proof of the correctness and effectiveness of the measures that were devised and introduced to alleviate the circumferential nonuniformity of furnace temperature. The temperature of the lining increased on the charging side of the furnace at the 25878-mm level in March 2014 and subsequently decreased to 400–450°C in May, which indicates that excess slag crust which had been present in that region collapsed when the gas distribution about the circumference of the furnace was changed.

Conclusion. An analysis was made of the temperature of the lining in the shaft and bosh of BF-3 beginning with its installation. The circumferential nonuniformity of the temperature distribution along the entire height of the furnace was due to changes in the smelting conditions over the 2.5 yr of the campaign: a change in the charging program, the use of different amounts of manganese-bearing materials in the charge, the number of closed tuyeres and their locations, the quality of the charge materials that were used, the chemical and component-by-component compositions of the iron-ore-bearing part of the charge materials, and their distributions across the furnace. Certain aspects of the changes in the temperature of the lining of BF-3 also indicate that there were changes in the direction of the gas flow inside the stock in the radial and circumferential directions when significant deviations occurred in the smelting parameters and the resistance of the stock increased. It was established that the decrease in smelting rate and the reduction in the quality of the charge materials that accompany an increase in the pellet content of the iron-ore part of the charge lead to increases in the height and area of the high-temperature zone – the zone that characterizes the position of the root of the viscoplastic zone.

The information which has been obtained here can be used both to substantiate choices for the diameter of the tuyeres, the number of closed tuyeres, and the locations of those tuyeres and to correct the regime that determines the circumferential distribution of the charge materials. When natural gas is employed on blast furnaces (or when a nonuniform distribution of pulverized-coal fuel may be formed about the circumference of the furnace), information on changes in the temperature of the lining can be used to control the distribution of fuel additives that are injected around the circumference.

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