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Introduction of Pulverized-Coal Injection at Yenakiieve Iron and Steel Works[1]

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Abstract—The introduction of pulverized-coal injection at Yenakiieve Iron and Steel Works in 2016 is described. The state of the lining of the blast-furnace shaft and hearth is analyzed. Requirements regarding the charging conditions are proposed so as to improve the durability of the cooling system and ensure accident-free furnace operation.

Keywords: blast furnace, pulverized coal, batch quality, charging program, shaft lining, hearth lining

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In recent years, pulverized-coal injection has been introduced at Ukrainian blast furnaces, usually without preliminary improvement in the cooling system, the charging system, or the level of automation and without imposing adequate requirements on batch quality. In such conditions, careful blast-furnace regulation is necessary, so that the operating staff can adjust the charging parameters and correct the blast on the basis of monitoring data. Note that effective operation with pulverized-coal injection not only imposes particular requirements on the quality of the coal, the iron ore, and the blast-furnace coke and on the design of the air tuyeres (their height, diameter, and inclination [1–3]) but also demands specific charging conditions—in particular, conical charging systems are inapplicable [4].

At Yenakiieve Iron and Steel Works (EMZ), in 2016, pulverized-coal injection was adopted at blast furnace 5 on March 1 and at blast furnace 3 on April 20. Because of the difficult conditions in the Donbas, plant specialists brought pulverized-coal injection on line while teleconferencing with specialists at Küttner (Germany), which supplied the equipment [5]. The basic design characteristics and monitoring instruments at blast furnaces 5 and 3 are summarized in Fig. 1 and in Table 1.

[1] Contributions to this research were made by A.G. Kovalenko, E.V. Belykh, and A.S. Khaibulaev of Yenakiieve Iron and Steel Works and V.V. Horupakha and N.M. Mozharenko of the Iron and Steel Institute.

The system for pulverized-coal preparation and injection includes a section for coal discharge and storage; a mixing section; a section for creating coal samples; a section for screening and additional crushing of the coal; a section for drying and grinding of the coal, equipped with two vertical mills (productivity 52.5 t/h); and a unit for pulverized-coal injection. The system also includes an oxygen–coal system for use after relative stabilization of the raw-material supplies. SS coal from Bachatsk coal mine was used for the production of pulverized coal at EMZ in 2016; its composition and properties meet global standards. The carbon content in the coal's working mass is 79.82%; the ash content is ≥8.5%; the content of volatiles is 22.1%; and the sulfur content is 0.20%. Two other important characteristics of the coal are the Hardgrove grindability *HGI* and the free-swelling index *FSI*. The grindability of the SS coal is extremely high. That permits very fine grinding and improves the operating conditions of the grinding system. Increase in *HGI* results in more complete combustion of the pulverized-coal particles, with accompanying reduction in energy consumption. Together with other factors, that permits increase in pulverized-coal consumption to 160 kg/t of hot metal or more. The *FSI* of the SS coal improves the gas dynamics at the base of the furnace and eliminates coking of the pulverized coal in the blast channel of the tuyeres.

On account of the challenging organizational and economic conditions in the region, the quality of the coke available at EMZ does not meet the standards for blast-furnace operation with pulverized coal. Table 2

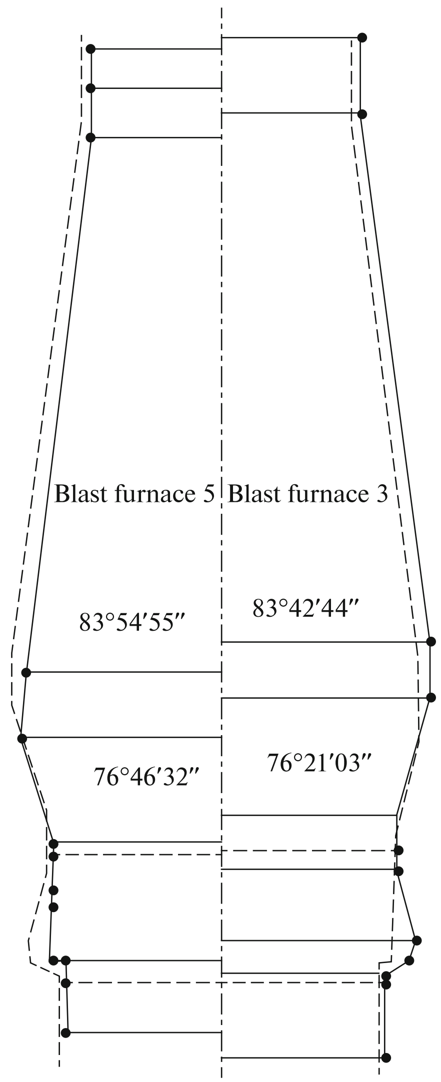

Fig. 1. Comparison of the profiles of blast furnaces 5 and 3 at Yenakiieve Iron and Steel Works.

presents those standards together with the actual coke characteristics during the introduction of pulverized-coal injection at blast furnaces 5 and 3, after the complete removal of natural gas from the blast before major repair with reinforcement of the blast-furnace shaft.

In addition, the composition of the iron ore used in this period of furnace operation was unstable. The content of pellets from Northern Iron Ore Enrichment Works ($CaO/SiO_2 = 0.05$) mixed with the sinter fluctuated within the range 10–75%. A shortage of locally produced sinter (basicity 1.4) with a high content of recycled material necessitated the use of additional sinter from Southern Mining and Processing Plant (basicity 1.6). The total iron content in the batch with limestone during the introduction of pulverized-coal injection was 54.8%.

Because of the poor batch quality and low rate of renewal of the coke packing, mild ore washing was required during the introduction of pulverized-coal injection with elevated blast-furnace productivity. At EMZ, to maintain satisfactory properties of the primary, intermediate, and final slag, Mn-bearing materials are used in the blast-furnace batch—in particular, manganese ore. The MnO reduces the viscosity of the intermediate slag and reduces the melting point of the iron-ore mixture in the batch. In the second stage, when the slag falls into the lower high-temperature zone, some of the manganese is reduced, with the gasification of carbon, facilitating the accelerated renewal of the coke packing and stabilization of the product heating in the base of the shaft.

Preliminary research showed that, in the blast furnaces at EMZ, when operating with poor-quality coke, increasing the MnO content in the batch by 1 kg/t of hot metal reduces the coke consumption by about 2.7–3.9 kg/t on account of the organization of mild washing of fine coke from the hearth and consequent stabilization of the hot-metal heating. In those conditions, the coefficient of manganese transfer to the hot metal is ~0.47 ± 0.03. By using Mn-bearing materials in amounts of ~25 kg/t of hot metal during the introduction of pulverized-coal injection, blast-furnace operation was improved and the scope for blast-furnace control during unstable batch supply was improved.

In the prevailing conditions of blast-furnace operation at EMZ, the introduction of pulverized-coal injection entailed change in the charging conditions. In the presence of pulverized-coal injection, the central gas distribution in the furnace may be insufficiently developed, while the peripheral gas flux may be extremely developed. Thus, increased furnace productivity is required with pulverized-coal injection. That may be ensured by improving the gas permeability in the peripheral zone. To ensure economical furnace operation, the development of the central gas flux must permit adequate regulation of the size of the axial coke vent. When using pulverized-coal injection with a large quantity of the slag at the product outlet (398 and 393 kg/t of hot metal for blast furnaces 5 and 3, respectively), the batch portions must be specially shaped so as to prevent access of the incompletely burned fuel particles to the primary and intermediate melt. Such particles would increase the likelihood of clogging of the hearth by nonmolten masses.

Therefore, in regulating the gas-flux distribution over the furnace radius with pulverized-coal injection so as to obtain optimal furnace performance at EMZ, the following measured are required.

(1) Maintenance of stable central gas distribution with a narrow axial coke hole; increase in the concentration of low-basicity raw materials in the vicinity of the pulverized-coal particles; and the development of a gas interchange between the periphery and the center.

Table 1. Blast-furnace characteristics and monitoring instruments

Characteristic	Blast furnace 5	Blast furnace 3
Startup date after reconstruction	June 29, 2007	October 18, 2011
Useful volume, m^3	1513	1719
Dates of shaft reinforcement after startup	October 2009; July 2011; November 2013; November 2016	June 2014; September 2016
Charge-hole radius, m	3.40	3.60
Charging system	Bell-type	Bell-less top
Height of cylindrical charge-hole section, m	2.70	2.30
Shaft height, m	16.40	16.20
Number of:		
hot-metal tap holes	2	2
blast tuyeres	20	24
stationary thermal probes above the batch surface	4	4
electromechanical probes	2	1
radar height meters	0	2
gas outlets	4	4
thermocouples:		
in the peripheral gas flux	16	16
at the lining of the shaft, bosh extension, and shoulders	40 + 16*	56
at the batch cooling system	30	–

* Repaired at the last shaft-reinforcement session; 16 thermocouples in the region of maximum thermal stress (above the second hot-metal tap hole) were additionally backed up.

Table 2. Quality of the coke used at blast furnaces 5 and 3 during the introduction of pulverized-coal injection

	Pulverized-coal injection, kg/t of hot metal	W	Ash content	S	M_{25}	M_{10}	>80	0–25	*CSR*	*CRI*
Blast furnace 5	110	3.47	10.96	0.90	88.04	7.33	9.36	3.15	49.2	33.5
Blast furnace 3	126	3.60	10.80	0.92	87.87	7.41	8.75	3.12	49.5	33.3
Operational requirements		≤0.5	<12	<0.6%	≥87.0	≤6.0	≤5.0	≤3.5	>60	<30

(2) Elimination of the localization of individual types of iron ore over the charge-hole cross section.

(3) Establishment of an iron-pre composition at the wall ensuring self-renewal of the coating in the lower part of the furnace shaft.

(4) Optimization of the gas permeability of the peripheral zone, without permitting excessive iron-ore influx, so as to prevent irregular batch descent.

On the basis of those principles, we have developed a charging program (based on the model system in [6]) and a system for forming the batch portions at blast furnace 3 (Fig. 2). The charging program must be modified in the light of the formation of an intermediate zone with challenging gas conditions (a zone with an increased ore load) during the introduction of pulverized-coal injection. This situation facilitates the development of an extreme peripheral gas flux, interference with the free flow of gas between the center and the periphery, and the formation of an occluded axial zone. Such a gas-flux distribution is found by the analysis of thermoprobe readings from the blast furnace [7]. The introduction of pulverized-coal injection also increased the lining temperature in the middle of the shaft and thermal loads on the cooling system in that zone.

The proposed changes in the charging program and the formulation of the batch portions permitted reduction in peripheral gas temperature by 13% on average (from 432 to 377°C) over the whole furnace height in the initial stages of the introduction of pulverized-coal

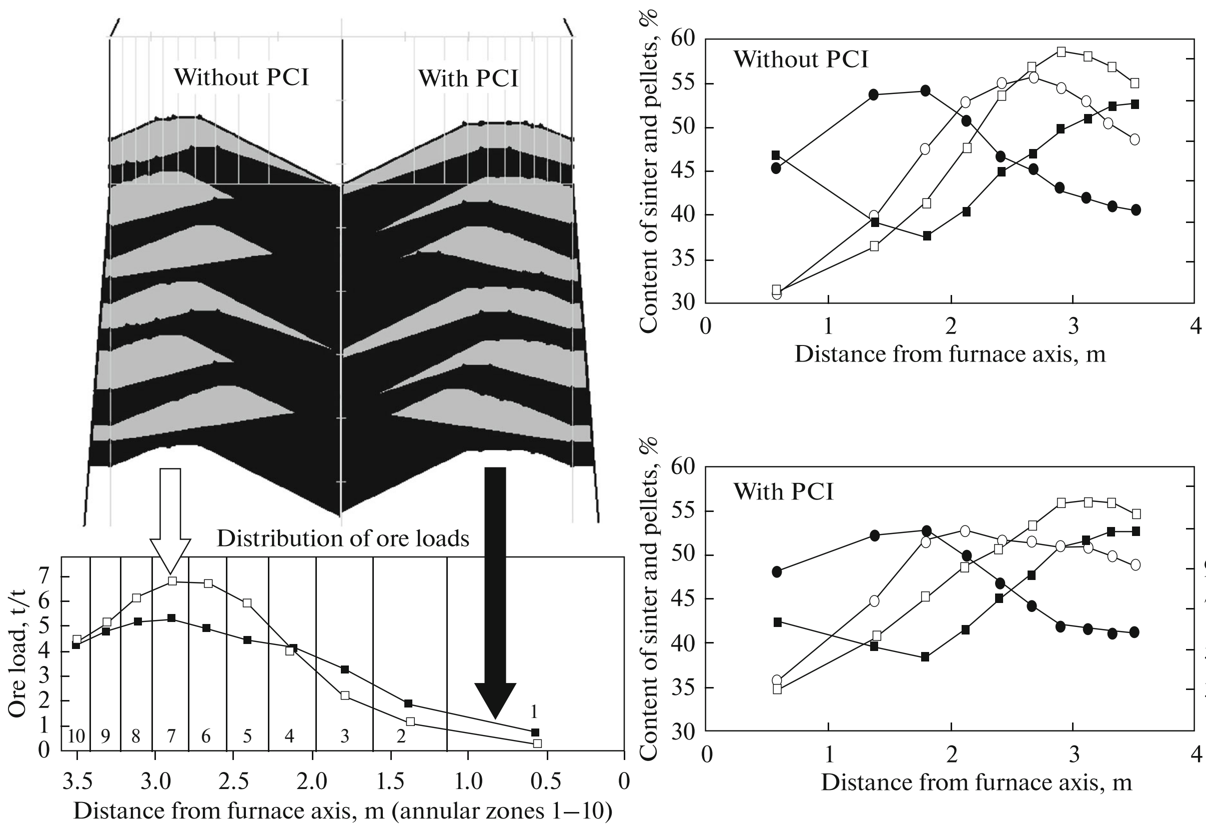

Fig. 2. Structure of the batch layers and distribution of the ore load and batch components over the furnace radius for rational charging at blast furnace 3 without and with pulverized-coal injection (PCI): (■) sinter; (●) pellets from Northern Iron Ore Enrichment Works; (□) sinter mass, t; (○) pellet mass, t.

injection at blast furnace 3 with no furnace lining. In addition, the azimuthal temperature nonuniformity was reduced by 11% (Fig. 3).

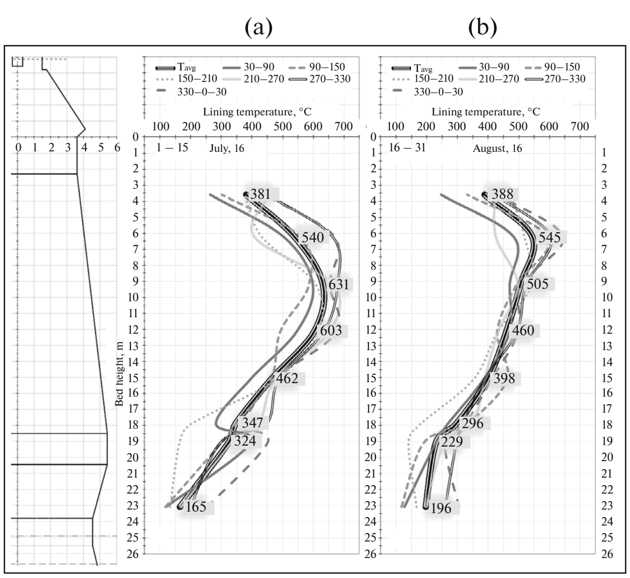

Fig. 3. Thermocouple readings at shaft lining, bosh extension, and shoulders of blast furnace 3 before (a) and after (b) adopting our charging recommendations.

At blast furnace 5, equipped with a conical charging system, the basic charging systems are COOC↓ and OOCC↓ (where C denotes coke and O denotes iron ore), which are used with different frequencies in the supply cycle. Analysis of the temperature in the peripheral zone of blast furnace 5 during the first five months of 2016 showed that, with increase in direct supply at high levels of the charge beds, zones of elevated temperature are formed, and slippage of the furnace coating is observed, primarily in the sector of the first hot-metal tap hole. We clearly need to select the optimal charging systems (in the light of factors such as the height of the batch bed) in order to address the periodic disruption of the gas distribution in the dry zone over the circumference of blast furnace 5 and also the need to create a moderately developed peripheral gas flux when using pulverized-coal injection with unsatisfactory furnace batch.

To identify the ore distribution over the radius of blast furnace 5, we calculate the distribution as a function of the charging system and the height of the batch bed (Figs. 4 and 5). We find that, with fluctuations of ±0.5 m from a height of 1.8 m (the level corresponding to charging with the large cone at the wall of the charge-hole safety plate), the ore crest approaches the furnace wall. The OOCC↓ charging system ensures a maximum in this zone. Hence, to prevent extreme ore delivery to

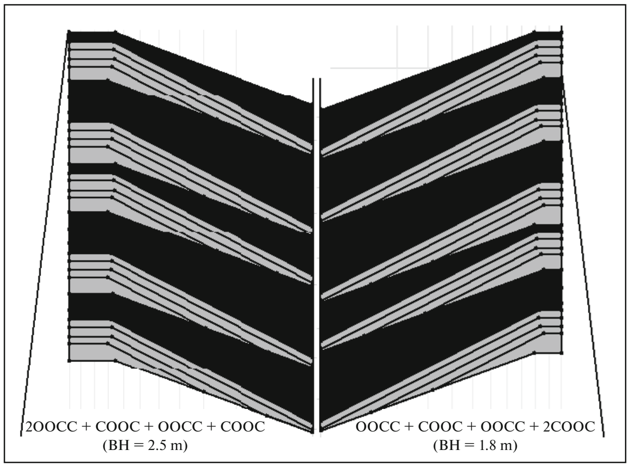

Fig. 4. Structure of the batch layers for the recommended charging systems in blast furnace 5.

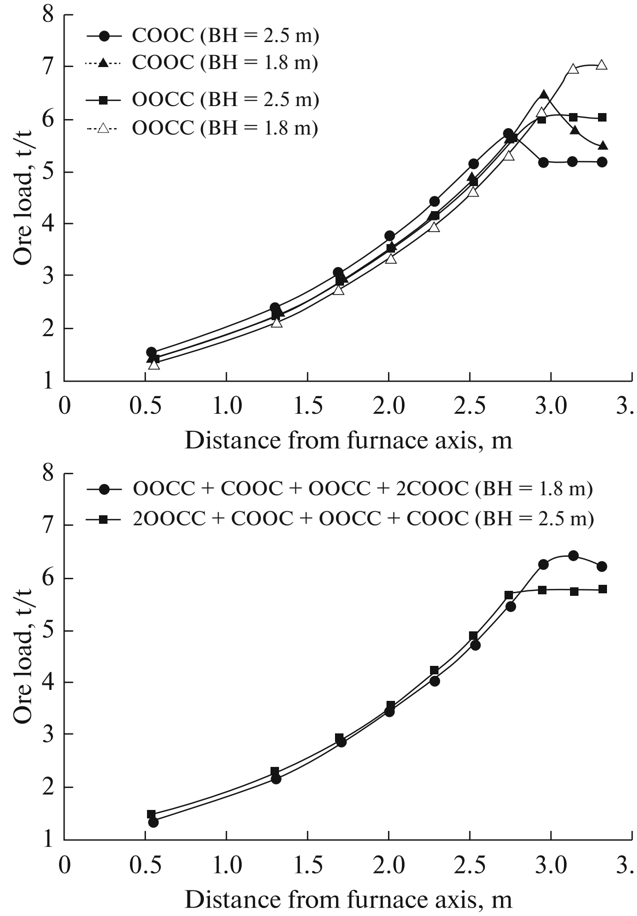

Fig. 5. Radial distribution of the ore load in blast furnace 5 with different charging systems, when the bed height (BH) is 1.8 and 2.5 m.

the peripheral zone with heights of 1.8 ± 0.5 m and 2.5 ± 0.5 m, we recommend the following charging systems: OOCC↓ + COOC↓ + OOCC↓ + 2COOC↓ and 2OOCC↓ + COOC↓ + OOCC↓ + COOC↓.

In other words, with reduced charge height, we need to increase the proportion of direct supply phases in the charging cycle; with increased charge height, by contrast, we need to increase the proportion of COOC↓ phases. This combination of charging cycles shifts the batch crest in the furnace to the intermediate and peripheral zone. That facilitates smooth batch descent in the given conditions. The proposed charging system may be used regardless of the development of the central gas distribution.

The interval between the last shaft reinforcement and the introduction of pulverized-coal injection was 27 months for blast furnace 5 and 22 months for blast furnace 3. Visual inspection of the furnace shafts showed an almost complete absence of lining. This indicates that the shaft thermocouples recorded the temperature of the peripheral gas flux during the introduction of pulverized-coal injection at blast furnace 3. At blast furnace 5, the lining thermocouples were restored at reinforcement in November 2016. On switching to pulverized-coal injection, the temperature in the peripheral zone of the furnace was assessed on the basis of the readings of thermocouples at the cooling units. Analysis of the thermocouple readings for blast furnaces 5 and 3 permits the following conclusions.

At blast furnace 5, with change in the thermal and gas-dynamic conditions, the greatest fluctuations are seen in the temperature of the cooling units at distances of 9.04 and 12.10 m from the air tuyeres; the temperature at the shoulders varies from ~50 to ~95°C. Rapid growth and small variation in temperature over the circumference at the shoulders indicates relatively limited transfer of hearth gas close to the cooling plates in that region and reliable support of the batch column. However, with sharp change in temperature, slippage of the coating from the bosh extension at the bottom of the batch is observed. The level of protection in this case remains satisfactory.

In the middle of the shaft and at the top in blast furnace 5, the temperature fluctuations are considerably smaller: 150–200°C over the circumference at the top of the furnace and up to ±50°C at each measuring point. At these levels, as at the lower levels, the temperature variation over the circumference is nonuniform. The cooler sectors of blast furnace 5 are at the batch-supply side; the hotter sector is close to the second hot-metal tap hole. That confirms the nonuniform gas temperature variation in this region.

In transient conditions, with increase in the oxygen content in the blast and in the blast temperature with the intensification of pulverized-coal injection and corresponding decrease in extent of the tuyere regions, the zone of unstable coolant temperature falls to the level of the shoulders, with relatively rapid heating (within ~3–7 days). Then, the temperatures steadily fall to a permissible level over the next seven days. At reinforcement of the shaft in late October (and early November) 2016, besides restoration of thermocouples in the shaft lining at blast furnace 5, two cooling plates were completely replaced; at 12 cooling units, burned-out tubes were replaced.

At blast furnace 3, thermocouples were placed in the shaft lining over the depth and over the circumference at a depth of 100 mm [8]. The thermocouples were established at six levels of the shaft and also in the bosh extension, at the shoulders, and in the tuyere zone. The thermocouple distribution around the furnace circumference was as follows: eight at the level of the shoulders, the bosh extension, and the three lower levels of the shaft; six thermocouples at each of the two higher levels; and four thermocouples at the upper level [8].

Analysis of the temperature variation at the lining (in the peripheral gas flux) in blast furnace 3 during the introduction of pulverized-coal injection leads to the following conclusions. With high rates of pulverized-coal injection (15–18 t/h), the temperature at two levels in the middle of the shaft increased from 215 to 550°C, on average. The temperature of the lining thermocouples in the lowest level of the shaft were characterized by small variation at the beginning of 2016. With the introduction of pulverized-coal injection, unstable temperature variation was observed at that height. In the second row of thermocouples at the bottom of the shaft, the opposite pattern was observed: stabilization of the temperature and its mean square deviation over the circumference with the introduction of pulverized-coal injection. This may indicate change in position of the root of the viscoplastic zone on switching from gas-free batch with wet blast at the beginning of 2016 to natural gas and then to pulverized-coal injection. With high rates of pulverized-coal injection, all the temperatures at the two levels at the base of the shaft increased from 215 to 390°C, on average.

At the bosh extension, the temperature in the lining increased by a factor of 1.8 (to 310°C) from the beginning of 2016 to the introduction of pulverized-coal injection. At the level of the shoulders, the temperature readings at the lining varied stably. That indicates a stable coating at the shoulders, as confirmed by visual inspection of the batch after injection. The increase in absolute temperature at the shoulders is slight: from 125 to 175°C.

Thus, at the middle and at the base of the shaft and at the bosh extension, we note significant change in absolute temperature of the lining and also in the mean square deviation over the circumference of blast furnace 3 in transient operating conditions, including the period when pulverized-coal injection was introduced. This may be attributed to change in position of the viscoplastic region and wear of the shaft lining. Note that, when high rates of pulverized-coal injection were adopted, the run was already two years old, and the furnace was due for the next reinforcement session. When using rational charging programs, operational reliability of the cooling system was achieved in blast furnace 3, in the absence of a shaft lining, and the furnace operated without incident. After reinforcement of the shaft of blast furnace 3 in September 2016, the temperature distribution of the lining equalized from the shoulders to the upper level of the shaft. The temperature increased from 100 to 200°C by January 2017.

The automatic control system of blast furnace 3 recorded the total thermal loads of the cooling system for the furnace as a whole and for individual zones. Analysis of those data for 2016 indicates that, during the initial introduction of pulverized-coal injection, the mean daily value sometimes reached 10 MW. On days with rates of pulverized-coal injection reaching 130–140 kg/t of hot metal, the thermal loads reached their highest value: 19.2 MW. In October 2016, when blast furnace 3 reached its planned daily output after repair, the total heat losses (6–9 MW) reached the level at the beginning of 2016, before the introduction of pulverized-coal injection. Note that the total thermal load of the cooling system depends primarily on the thermal loads in the middle zone. That is consistent with the analysis of the lining temperature in the shaft, which indicates that the middle of the shaft is the region over the height of blast furnace 3 with the greatest thermal stress, on account of two factors: the increased distance from the axes of the air tuyeres to the bend in the profile of blast furnace 3 (the bottom of the shoulders; see Fig. 1); and the air-tuyere design employed at EMZ.

With severalfold increase in the total thermal load of the cooling system, we may judge the degree of lining wear in the shaft, bosh extension, and shoulders on the basis of monitoring data for the lining temperature and plan appropriate measure to prevent failure of the cooling plates in the zone with high thermal stress. The considerable increase in the thermal load may explain the high fuel consumption required to compensate the heat losses at the coating.

From the state of the well in the blast furnaces, we draw the following conclusions. From the beginning of pulverized-coal injection at blast furnace 5, the temperature in the central part of the well rose slightly but did not observe the maximum values previously observed. That indicates a lack of lining wear. The fluctuation in the lining temperature indicates a stable coating layer in the well. The thermal loads in the sector of the well under the hot-metal tap hole remain at the level before the introduction of pulverized-coal injection (~2 kW/m^2). After the onset of pulverized-coal injection at blast furnace 5, the lining temperature in the peripheral part of the hearth and at the well between the third and eighth thermocouple levels remained largely unchanged. Hence, the residual lining thickness was unchanged; the lining wear was no more than 20% on average. After the onset of pulverized-coal injection, measurements of the thermal loads were made at the cooling system of the hearth and well. They showed that the thermal loads at the cooling units of the well did not exceed the maximum values recorded in the 2007 furnace run. Because of the deficiencies of the automated monitoring and the trend to increase in thermal load at the cooling units in the hearth, regular measurements of the thermal loads at the cooling units of the hot-metal tap holes and the lower and upper hearths are recommended at blast furnace 5.

The well lining in blast furnace 3 consists of various refractories from GrafTech International (United States) and NDK (Japan). The working surface of the well is protected by a ceramic casing produced by Saint Gobain International (France). From the onset of pulverized-coal injection at blast furnace 3, the thermal load in the center of the well remained at the previous level: ~1.5 kW/m^3, on average. There was no lining wear in the center of the well; its surface was covered by a coating layer. Over five years of operation at blast furnace 3, the thermal load at the peripheral cooling units was stable and no more than 20 kW (at the upper and lower well) and 30 kW (at the upper and lower hearth). After the onset of pulverized-coal injection, the lining temperature and the thermal load on the cooling units remained unchanged (even in the zones with hot-metal tap holes). The lining thickness in the peripheral region of the hearth and well outside the sector with the hot-metal tap holes remained at the design level; the lining was protected by a coating layer. In the sector with the hot-metal tap holes, permissible wear of the ceramic layer (no more than 25%) was noted, on account of erosion by the metal and slag fluxes.

CONCLUSIONS

After the introduction of pulverized-coal injection in blast furnaces at Yenakiieve Iron and Steel Works with variable batch and with poor-quality coke, the pulverized-coal consumption in 2016 was 130 kg/t of hot metal on average, in the case of rational charging programs, portion formation, and selection of the slag conditions.

By ongoing monitoring of the shaft lining in the blast furnaces by means of thermocouples in the lining and at the cooling units, as well as observations of the thermal load at the cooling system, timely measures may be taken to apply coating to the lining and correct the distribution of batch components over the furnace radius and circumference.

The proposed changes in the charging programs and portion formation permitted reduction in the temperature of the peripheral gas flux by 13%, on average, over the whole height of blast furnace 3 during operation with no lining in the initial stages of pulverized-coal injection. In addition, the azimuthal temperature nonuniformity was reduced by 11%.

The use of rational charging during the introduction of pulverized-coal injection permitted operational reliability of the cooling system before shaft reinforcement and accident-free furnace operation.

In the initial stages of pulverized-coal injection at EMZ, the thermal loads at the well of the blast furnaces were unchanged.

Analysis of the state of the hearth and well in blast furnace 3 shows that the use of a ceramic covering is effective. After five years of operation, its wear is no more than 25% in the sector with the hot-metal tap holes.

REFERENCES

1. Podkorytov, A.L., Kuznetsov, A.M., Dymchenko, E.N., et al., Technology for preparing coke for blast smelting and its efficiency, *Metallurgist*, 2009, vol. 53, nos. 7–8, pp. 460–468.
2. Podkorytov, A.L., Kuznetsov, A.M., Padalka, V.P., et al., Testing and optimization of the technology at Blast Furnace No. 5 of the Enakievo Steel Plant, *Chern. Metal.*, 2008, no. 11, pp. 59–71.
3. Kuznetsov, A.M., Padalka, V.P., and Zubenko, A.V., Improvement of the technology of blast-furnace smelting, *Stal'*, 2007, no. 11, pp. 6–7.
4. Bol'shakov, V.I., Use of ballast furnace smelting technology with carbon powder inflow, in *Fundamental'nye i prikladnye problemy chernoi metallurgii* (Fundamental and Applied Problems of Ferrous Metallurgy), Kyiv: Naukova Dumka, 2011, no. 23, pp. 30–36.
5. http://uaprom.info/news/152518-ustanovku-put-enakievskom-metzavode-zapustili-skajpu-glava-metinvesta.html.
6. Semenov, Yu.S., Shumelchik, E.I., Vishnyakov, V.I., et al., Model system for selecting and correcting charging programs for blast furnaces equipped with a bell-less charging apparatus, *Metallurgist*, 2013, vol. 56, nos. 9–10, pp. 652–657.
7. Bol'shakov, V.I., Semenov, Yu.S., Shumelchik, E.I., et al., The use of temperature information over the surface of the charging bed to control blast furnace smelting, *Metall. Gornorudn. Prom.*, 2015, no. 3, pp. 2–7.
8. Semenov, Yu.S., Mozharenko, N.M., Horupakha, V.V., et al., Effect of the fuel, raw materials, and process condition on the behavior of temperature change in a blast-furnace lining, *Metallurgist*, 2015, vol. 59, no. 3, pp. 290–299.

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