INTRODUCTION INTO MMK BLAST FURNACES OF AN AUTOMATED SYSTEM FOR SMELTING CONTROL, OPTIMIZATION, AND PREDICTION

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Results are provided for work conducted in the Magnitogorsk Metallurgical Combine blast-furnace workshop for production satisfaction of a blast-furnace automatic control system by stagewise introduction of local systems combining into one automated system for control, optimization, and prediction of blast furnace smelting (ASCOP BF). Using mathematical models and special ASCOP BF algorithms for each blast furnace, there is continuous automatic monitoring of radial and circumferential gas distribution in the bell, circumferential gas distribution in the furnace hearth, material and thermal balances of smelting and furnace heating; optimization of the smelting gas dynamic regime, radial and circumferential gas distribution in the bell, circumferential gas distribution in the furnace hearth, smelting recovery processes, thermal state of a furnace and melting zone parameters; prediction of silicon content in cast iron. The order of conducting operations is proposed and substantiated for achieving maximum productivity and minimum coke consumption with given smelting raw material and operating conditions. It is shown that the mathematical models used in the system by the process described are ready for use in blast furnace automatic control systems already created for blast furnaces in other metallurgical enterprises in order to achieve the best smelting indices.

Keywords: *automated system, blast-furnace smelting, control, optimization, forecast, increased efficiency, expanded implementation.*

Results are presented in this article for work carried out since 2006 at the Magnitogorsk Metallurgical Combine (MMK) blast-furnace workshop for improvement of automatic control systems created for blast-furnaces in the course of stagewise introduction of an automated system for control, optimization, and prediction of blast furnace smelting (ASCOP BF). A list of local systems within the ASCOP BF and stage of their introduction are given in Table 1. Results of introducing them have been described in [1, 2].

Features of the work are stagewise introduction of local ASCOP BF systems; connection of systems to the automatic control system created using engineering facilities; transfer of calculated results of a system to master workstations of all furnaces and workshop management; functioning of the systems developed in an on-line regime with automatic delivery of recommendation for improvement of blast-furnace smelting; use of experience of creating automated systems for blast

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TABLE 1. Composition of a Group of ASCOP BF Systems Introduced into MMK Blast Furnaces

| Local systems	Furnace number	Year introduced
Blast-furnace smelting control		
1.1 – radial gas distribution in bell	2, 4, 6, 9, 10	2006
1.2 – circumferential gas distribution in bell	2, 10	2011
1.3 – circumferential gas distribution in hearth	2	2011
1.4 – smelting material and thermal balances	2; 10; 4, 6, 9	2013; 2016; 2017
1.5 – furnace heating	All furnaces	2008
1.6 – CCU operating regime	2, 10	2010
Optimization		
2.1 – smelting gas dynamic regime	All furnaces	2008
2.2 – radial gas distribution in bell	2, 4, 6, 9, 10	2011
2.3 – circumferential gas distribution in bell	2, 10	2011
2.4 – circumferential gas distribution in hearth	2	2011
2.5 – smelting recovery processes	2; 10; 4, 6, 9	2013; 2016; 2017
2.6 – furnace thermal state	All furnaces	2009
2.7 – melting zone parameters	2; 10; 4, 6, 9	2014; 2016; 2017
Prediction		
3.1 – cast iron silicon content	2	2011
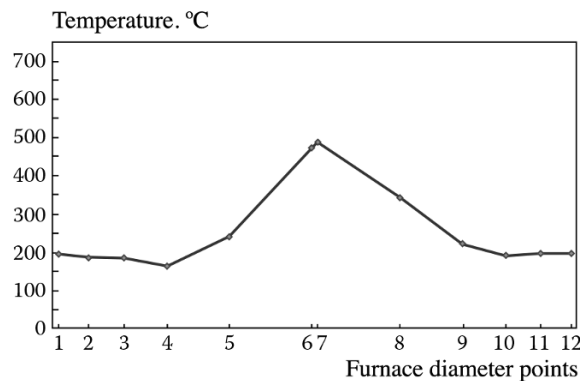
Fig. 1. Gas temperature distribution over BF-6 diameter per day (00:00, 05.15.2016 – 00:00, 05.16.2016).

furnaces and their upper level in the USSR, CIS countries, and overseas, obtained during operation at VNIPI SAU (Moscow), Siemens (Germany), and at AKOMM (Moscow) created in 1992.

Group of Blast-Furnace Control systems. The tasks resolved in this group of systems are both of importance independently, and are used in calculations for groups of Optimization and Prediction systems. A system for monitoring radial gas distribution in the blast-furnace bell equipped with a CCU (see 1.1 in Table 1) uses the following sensors:

– stationary radial multipoint thermocouples (RMT) of AKOMM [1, 3]. At the request of a user on the screen furnace video-terminals Nos. 2, 4, 6, 9, and 10 temperature trends and average curves (Fig. 1) are provided for recent periods: "output"
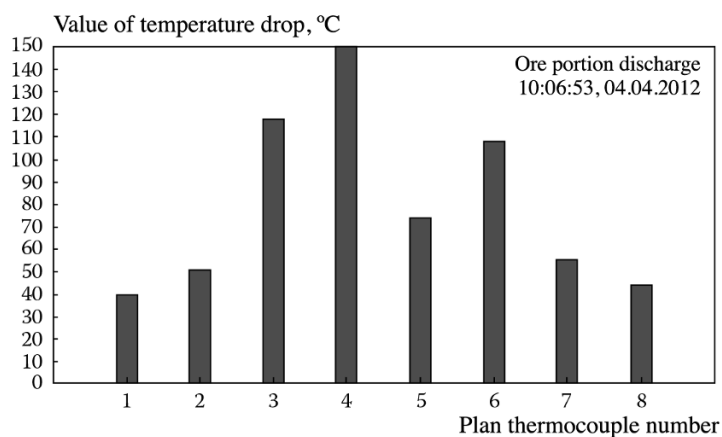
Fig. 2. Gas temperature below gas offtakes. Absolute values of BF-10 reading changes.

(furnace operating period from closure to closure of the iron tap-hole for adjacent tappings, a shift, day, and week for all furnaces fitted with RMT;

  • peripheral AKOMM thermocouples above the charging level (PTA), installed in the same place as RMT;
  • in the tapered row of bell protective plates (BPP). Their junctions are located at the same distance from the vertical part of the BPP, which are also the first points of the TMT; and
  • furnace gas outlet thermocouple (GOT).

The importance of the monitoring system for circumferential gas distribution in the furnace bell (see 1.2 in Table 1) arose particularly in view of introduction of the chute type CCU. In addition to the peripheral thermocouple beneath the BPP (PTP) and a thermocouple of the furnace gas outlet (FGO) in five furnaces, within which a CCU was installed, eight PTA were installed. For an example, data are given in Fig. 2 for the reduction in PTA readings after charging iron-ore material (IOM) to different point of the bell circumference. They point to non-uniform IOM distribution over the bell circumference in this case.

It was assumed that for operative control of the circumferential gas distribution in the furnace hearth (see 1.3 in Table 1) it is most expedient to use information about thermal action of the tuyere location for an air tuyere [4]. This problem was resolved by means of sensors for water flow rate (in order to determine heat exchange) for cooling air tuyeres, installed for monitoring burnout, and a mathematical model (MM) developed for calculating the temperature at the tuyere location (T_{tl}) [4]. Calculation algorithms make it possible for actual furnace operating parameters and data for the amount of heat removed from a tuyere with cooling water to determine the T_{tl} for each tuyere location (Fig. 3).

The monitoring system for material and heat balances (see 1.4 in Table 1) is intended for operational, on the theme of melting process, calculation of material and heat balances (MHB). The aim of performing MHB calculations (Tables 2 and 3) is use of the amounts of their discrepancies and some items of balances for analyzing occurrence of melting processes and recognition of deviations from standards for earlier stages.

In order to monitor furnace heating (see 1.5 in Table 1), MM are used for gas dynamic heat and mass transfer processes in the furnace two-layers zones [5, 6]: the tuyere zone, and the zone of final melted product composition formation and heating (zones III and IV in Fig. 4). The model considers the following data: formation and dimensions of tuyere locations (1); combustion of coke and its replacements (2); passage of molten products through the tuyere location and oxidation of previously reduced iron within them (3); distribution of heat liberated as a result of oxidation of iron between melt and gas products (4); transfer of heat radiated from gases in the shell of the tuyere location and melt (5); thermochemical processes occurring in the "finishing" zone, including secondary iron reduction, oxidized in tuyere locations, and direct reduction of iron impurities (6); physical heat loss, including with tuyere cooling water (7).

The most complex problems for solution were 1, 3, 4, and 5. In order to calculate the extent of the tuyere location L_{tl} (problem 1), an expression was used provided in [6]. The possibility of calculating L_{tl}, and also solution of problems 3, 4 [7], and 5 [8] makes it possible to determine complex parameters (CP) specifying processes in tuyere locations. Among CP there
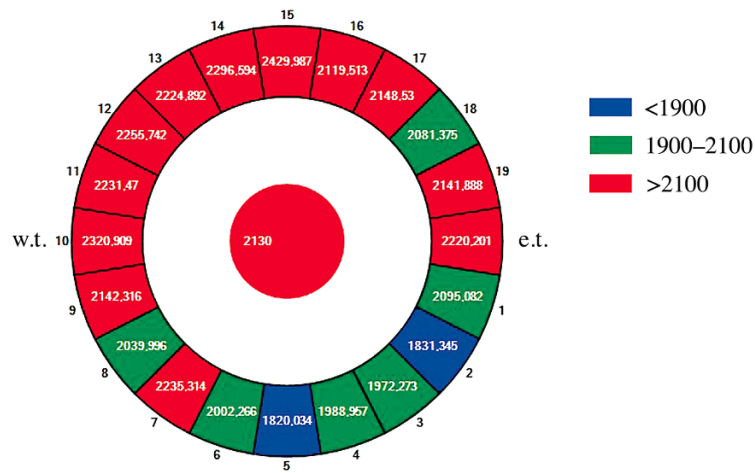
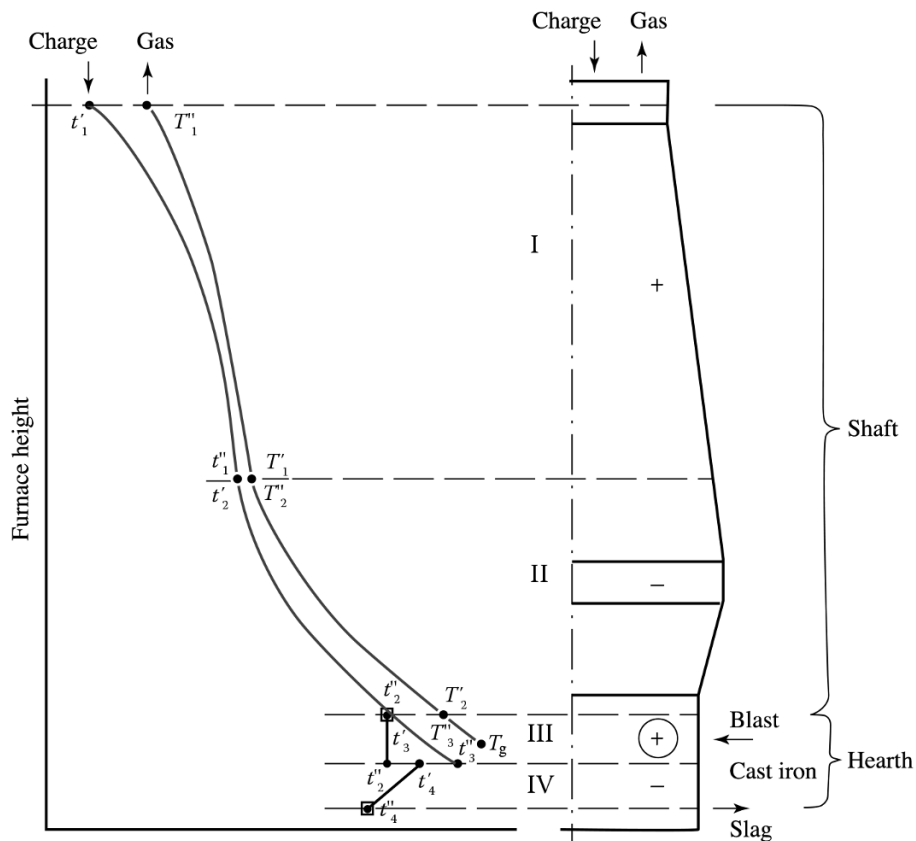Fig. 3. Gas temperature in tuyere locations: w.t. is western iron tap-hole; e.t is eastern iron tap-hole.

Fig. 4. Distribution of heat exchange zones (I–IV) material (t) and gas (T) temperatures over furnace height (from charging level to cast iron tap-hole): □) blast furnace thermal condition criteria; I, II, III, IV) heat exchange zones; +, –) processes occurring with heat liberation (absorption).

are: temperature of molten product at the entry of the tuyere zone (t_3'), or at the outlet from the furnace (shaft) (t_2''), since they are equal numerically; temperature of the tuyere location shell (t_{shell}); balanced gas temperature in the tuyere location (T_3''), entering into heat exchange with charge materials in the second stage, and differing significantly with respect to physical
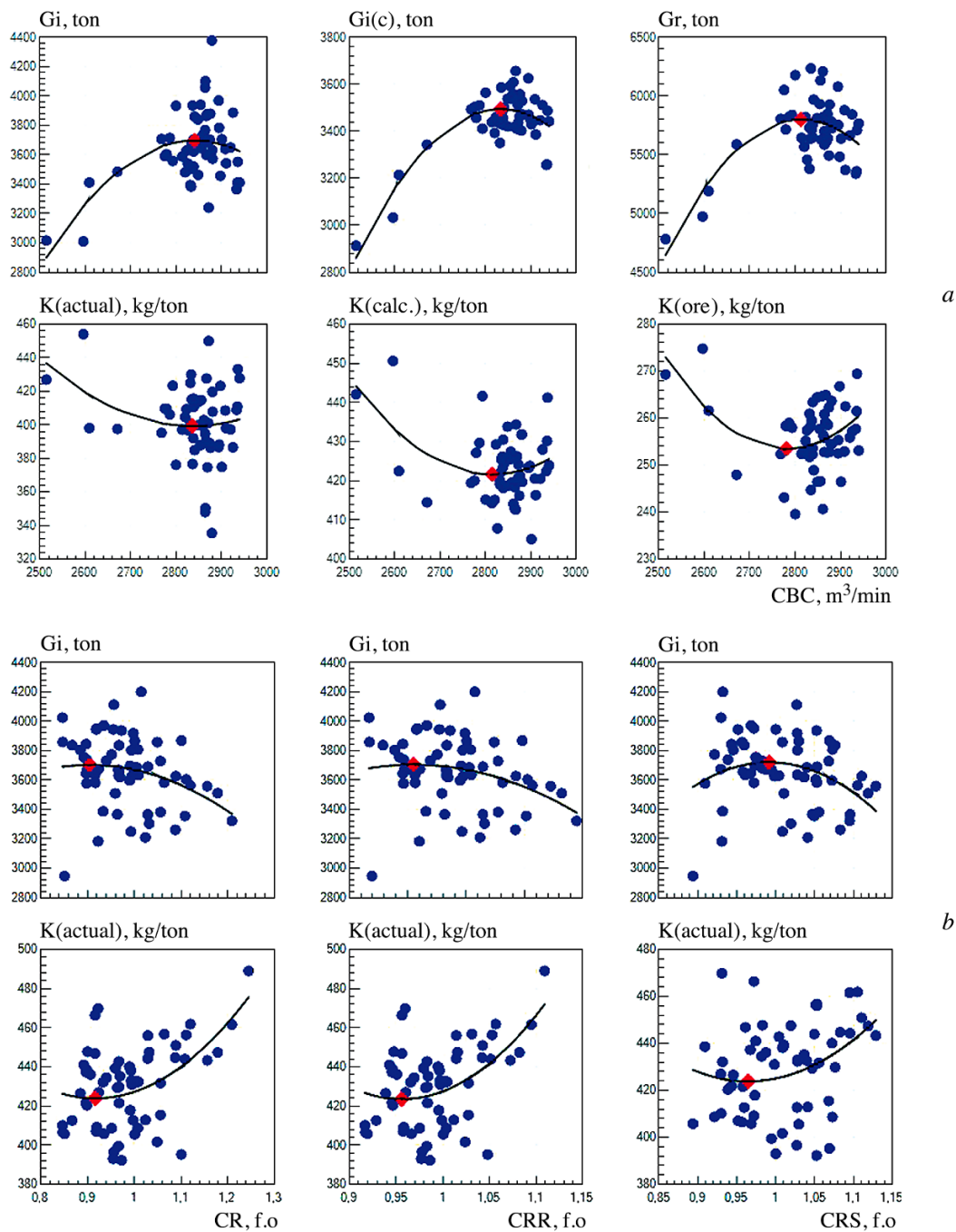
Fig. 5. Dependence of operating parameters for days: *a*) BF-1 (05.09.2016–07.08.2016); *b*) BF-6 (06.01.2016–07.31.2016): ●) starting data; ——) regression; ◆) extremum; Gi is actual iron smelted, ton/day; Gi(c) is calculated iron smelted ton/day; Gr is iron-ore material (IOM) smelted, tons IOM/day; CBC is cold blast consumption.

nature from the theoretical combustion temperature; temperature of melt product at the outlet from the tuyere location (t_3''); temperature of melt products at the inlet to the "finish" zone (t_4'); temperature of melt products at the outlet from the "finish" zone (t_4'').

Group of Blast-Furnace Smelting Optimization systems. Improvement of a blast furnace as a unit for smelting metal consists in that all the main (gas dynamic, mass and heat exchange, smelting) processes within it have optimum values and

TABLE 2. Results of Calculating BF-2 Material Balance per Day (00:00, 05.16.2016 – 00:00, 05.17.2016)

MB items	Value, kg/ton
Agglomerate specific consumption	1053.5
pellets	664.8
coke	445.5
blast (calculated)	1225.2
natural gas (actual)	77.7
Input part of balance	3466.7
Specific calculated output of cast iron	1000.0
slag	323.2
dry bell gas	2002.7
Specific direct reduction moisture	98.1
Consumed part of balance	3424.0
Material balance discrepancy, %	1.2

TABLE 3. Results of Calculating BF-2 Heat Balance per Day (00:00, 05.16.2016 – 00:00, 05.17.2016)

HB item	Value, kcal/kg	Fraction, %
Amount of heat added with blast	370.3	40.7
Amount of heat from coke carbon combustion	494.8	54.4
Amount of heat from natural gas combustion and added with natural gas	44.4	4.5
Heat input	909.4	100.0
Amount of heat for direct reduction of iron in mixed reduction zone	274.2	30.1
Amount of heat going into indirect iron reduction in zones of indirect and mixed reduction	45.5	5.0
Tota amount of heat for direct reduction of cast iron impurities in the "finishing" zone	45.9	5.0
Cast iron heat content	310.6	34.1
Slag heat content	142.2	15.6
Bell gas heat content	73.0	8.0
Heat lost with tuyere cooling water	109.3	12.0
Heat lost to surroundings	4.4	0.5
Heat consumption	914.0	100.5
Heat balance discrepancy	–4.6	–0.5

blast-furnace smelting efficiency will be better the closer they are to the optimum level. In order to resolve this problem, calculation models are used providing calculated restoration of optimum regimes.

The system for optimizing blast consumption (see 2.1 in Table 1) is intended for determining that amount of blast fed to a blast-furnace with which there is formation of the optimum volume of gas flow for a specific raw material and operating conditions. In this case, criteria for optimization may be either minimum coke consumption, or maximum furnace productivity. The choice of optimization criterion is made by workshop production personnel proceeding from workshop requirements and specifications for subsequent cast iron conversion. An example is given in Fig. 5 for determining the optimum blast consumption for BF-1.
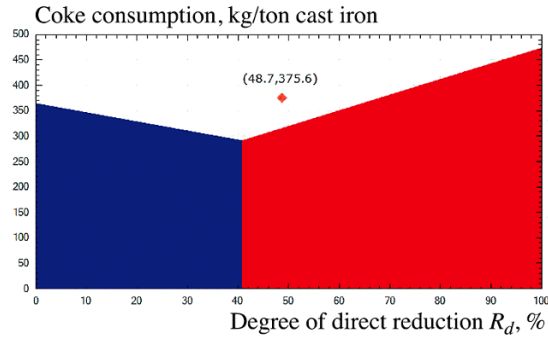
Fig. 6. Diagram of BF-10 direct reduction for days $(00:00, 05.15.2016 - 00:00, 05.16.2016)$.
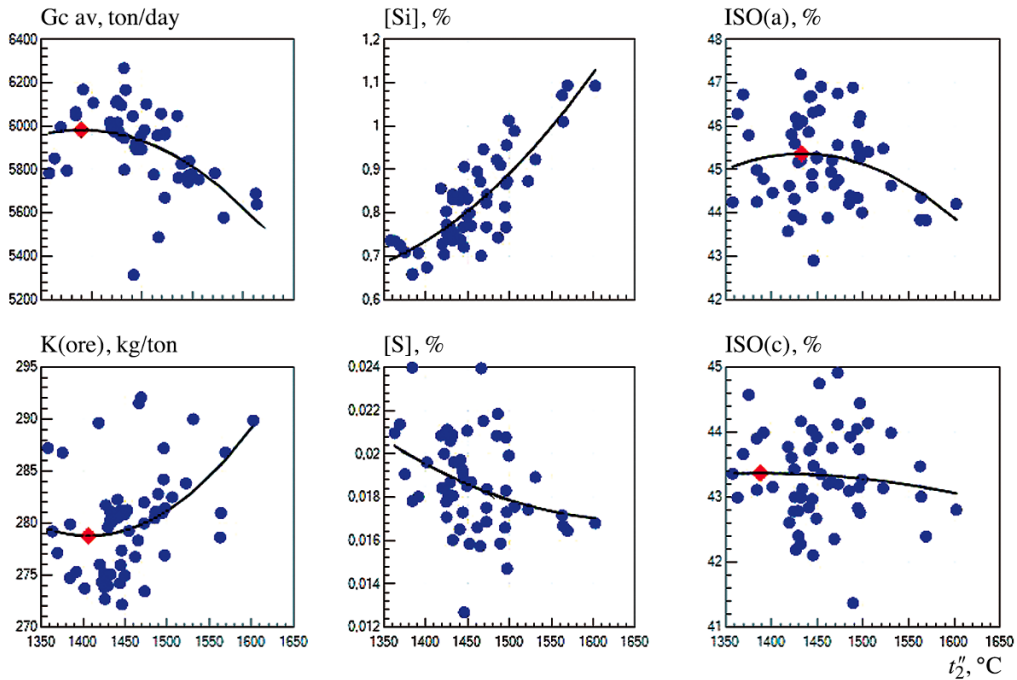

Fig. 7. Dependence of BF-2 operating parameters for days from 06.13.2015 to 08.12.2015: ●) starting data; ——) regression; ◆) extremum.

The system for optimizing radial gas distribution (RGD) (see 2.2 in Table 1) occupies an important place in blast-furnace smelting management. In order to control RGD in the furnace bell, the uncooled AKOMM RMT is most suitable [1, 3]. Apart from monitoring radial gas distribution in the furnace bell RMT readings are used for controlling the shape of the melting zone (MZ) by means of a two-dimensional mathematical model (TMM) [9].

For quantitative evaluation of the RGD in the furnace bell from TMT readings, two radial inequality coefficients were used:

$$CR = t_p/t_c, \text{ fract. one} \quad \text{and} \quad CRR = t_p/t_r, \text{ fract. one},$$

where $t_p = 0.4t_1 + 0.4t_2 + 0.2t_3$ is gas temperature in the "peripheral" part of the bell, °C; $t_c = 0.2t_3 + 0.4t_4 + 0.4t_5$ is gas temperature in the "central" part of the bell; $t_r = 0.2t_1 + 0.2t_2 + 0.2t_3 + 0.2t_4 + 0.2t_5$ is temperature over the furnace radius, °C; $t_1 - t_5$ are thermocouple readings at five equal rings over the area of the bell (in the furnace-circle center), reckoned from the periphery to the center.

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TABLE 4. BF-2 Tuyere Location Temperature Distribution

Parameter	Tuyere temperature distribution (°C)																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Av.
Before natural gas redistribution 11.19.2011 (from 12:45 to 12:50)																					
TL temperature, °C	2001	1762	1987	1929	1900	1970	1787	2166	2231	2060	2035	2204	2081	2022	2185	1946	1841	1876	2012	2069	2003
Prescribed for PG		↗					↗	↗	↗			↗			↗		↗	↗			
After natural gas redistribution 11.19.2011 (from 12:55 to 13:00)																					
TL temperature, °C	2006	1950	1987	1935	1907	1980	1920	2030	2070	2021	1998	2090	2076	1960	2061	2009	1947	1973	2070	2072	2003
Prescribed for PG																					

In addition, another coefficient is used:

$$CRS = t_{pa}/t_{bg}, \text{ fract. one,}$$

where t_{pa} is average temperature of peripheral gas for readings of the values of TPU thermocouples, °C; t_{bg} is average bell gas temperature from readings of values of TPG thermocouples, °C.

Comparison of coefficients for radial inhomogeneity (CR, CRR, and CRS) and parameters specifying MZ shape [9] with final smelting indices (furnace productivity and specific coke consumption) showed that for MMK conditions MZ parameters have the most effect on the latter [9].

A system for optimizing circumferential gas distribution (CGD) in the bell (see 2.3 in Table 1) for blast-furnaces equipped with a shute type CCU is especially important. Monitoring of the reduction in PDN indices after loading the iron-ore part of a charge (IOC) at different points of a bell circumference (see Fig. 2), makes it possible to approach CGD optimization.

The system for optimizing circumferential gas distribution in a furnace hearth (see 2.4 in Table 1) accomplishes levelling of the tuyere location temperatures t_{tl} (see Fig. 3) by means of heat exchange sensors installed in all of the BF-2 air tuyeres and regulation of natural gas supply to tuyeres (hydrocarbon, fuel oil, etc.) (Table 4).

The system for optimizing smelting reducing processes (see 2.5 in Table 1) is intended for determining the optimum ratio of indirect (R_i) and direct (R_d) iron reduction in a BF, with which the minimum coke consumption is achieved. Points of intersection of lines for the dependence of coke consumption on R_d as both a reducing agent and heat carrier obtained as a result of calculations determine the minimum possible coke consumption (Fig. 6).

A system for optimizing the furnace thermal condition (see 2.6 in Table 1) is aimed at resolving a more complex problem of controlling blast-furnace smelting. Of what does complexity of this system consist? It is well known that in order to resolve any optimization problem it is necessary to know its criteria. In view of features of heat exchange and reduction processes over a furnace height (from the charging level to the iron tap-hole) there are two criteria [3]: temperature of materials for input from a "charge" (shaft, bosch, and shoulders) of a furnace (t_2''); temperature of melting products at the outlet from the furnace "hearth" (t_4''). This also causes complexity for controlling the BF thermal condition. The presence of two criteria is determined by the fact that a blast-furnace from the charging level to the iron tap-hole is separated into four zone of heat- and mass-transfer (see Fig. 4) within which processes occur with different final thermal effects.

In order to determine the optimum thermal condition of a furnace, the system fulfils the following operations: continuous monitoring of current values of t_2'' and t_4''; determination of optimum values of t_2'' and t_4''; comparison of current and optimum values of t_2'' and t_4''; choice for level and sign and difference between current and optimum values for each criterion of control effects "from above" (change in coke consumption) and "from below" (change in blast parameters in order to achieve the optimum
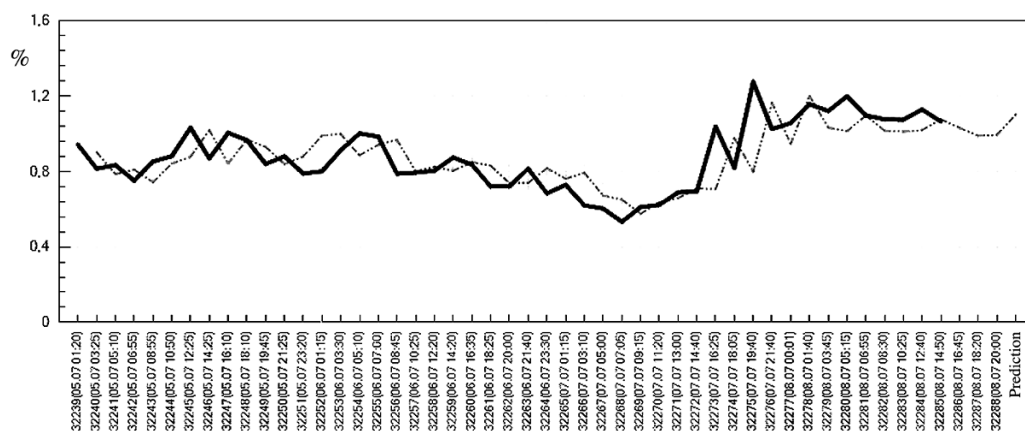
Fig. 8. Change in silicon content in BF-2 cast iron in period from 07.05.2016 to 07.08.2016: - - -) cast iron predicted Si content ([Sipr]), %; ——) cast iron actual Si content ([Si]), %.

furnace thermal condition. Optimum values of t_2'' are determined from results of operating the system after determining extremes for the dependences of coke consumption and furnace productivity in t_2'' (Fig. 7).

Research by the authors has also shown that an important factor sometimes having a decisive effect on furnace operation is material temperature at the inlet to the tuyere location (t_3''). Exceeding its value may lead to mass burning of air tuyeres [10].

Results of functioning of the parameter monitoring and optimization system for melting zones (see 2.7 in Table 1) in MMK BF are given in [9].

A system for predicting silicon content in cast iron (see 3.1 in Table 1) is intended for predicting cast iron silicon content of forthcoming tapping using a self-adjusting (from results of operation) statistical model for data about the temperature of all tuyere locations (see Fig. 3), average for the period from closing the preceding to closing the next tapping, and about silicon content in cast iron of the last two tappings. Results of this calculation are given in a video-chart "Charge in Si content in cast iron" (Fig. 8).

Conclusion. In blast furnaces of MMK, work has been carried out for technological satisfaction of the control system created with stagewise introduction of local monitoring systems, optimization and prediction of blast-furnace smelting indices, combined into an automated system for control, optimization, and prediction of blast-furnace smelting (ASCOP BF).

The ASCOP BF for each blast furnace using mathematical models and special sensors provides *continuous automatic monitoring* of radial and circumferential gas distribution in the bell, circumferential gas distribution in the furnace hearth, material and thermal balances of furnace smelting and heating; *optimization* is accomplished for a gas dynamic smelting regime, radial and circumferential gas distribution in the furnace hearth, melting reduction processes, furnace heat condition, and smelting zone parameters: it gives a *prediction of cast iron silicon content*.

This helps blast-furnace production personnel to control smelting effectively in order to achieve maximum productivity and minimum coke consumption with given smelting raw material and operating conditions.

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