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Substitution of Coke and Energy Saving in Blast Furnaces

Part 4. System Analysis of the Processes Under Influence of the Complex of Parameters

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Abstract

It was studied the influence of individual parameters and complex of factors on consumption of coke and found that use of the offered modes will allow to cut expenses coke to 190-200 kg/t of pig-iron on BF-9 AMKR and BF-5 "Severstal". Use of effective technology of pulverized coal injection should be accompanied by the development of additional and alternative technologies. In particular, attention should be drawn on injecting of coke-oven gas and the products of gasification of low-grade coal, as well as the charging in blast furnaces of specially prepared lump anthracite.

Key words: Blast furnace; Modeling; Ring radial zones; Vertical temperature zones; Overall balance; Coke rate; Productivity; Natural gas; Coke-oven gas; Blast temperatures; Oxygen contents; Pulverized coal

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INTRODUCTION

Consideration of the blast furnace, from the standpoint of system analysis requires consideration of all of its inherent properties exhibited as with variations in individual parameters, and at change of the complex of parameters and conditions of the heat. Another essential requirement of the system analysis is the interrelatedness of parameters, which is implemented through the adequacy of the models of processes. Proceeding from this, before presenting the results of the study, it showed a discussion of the methodological problems of mathematical modeling.

1. MATHEMATICAL MODELING AS A BASIS OF SYSTEM ANALYSIS

As shown earlier, the development of the technology of blast-furnace during the whole six-century period was closely connected with the cognition of regularities of its processes, and in the early 4th century—at the empirical level (Tovarovskiy, 2009, p.768; Tovarovskiy, 2012; Tovarovskiy, 1987, p.192). Only by the middle of the 19th century the study of the processes has gained importance. In the subsequent 1, 5 century on the basis of achievements of fundamental science and numerous experimental studies in laboratories and blast furnaces created a system of knowledge, suitable for practical use, significant of which received a vivid characterization of L. Boltzmann: "Nothing is more practical than a good theory".

By the end of the twentieth century has accumulated a great amount of knowledge, some of which repeat each other and other contradict the findings of similar studies. The explanation of the results with the former position is more difficult. This situation is due to the fact that the accumulation of knowledge outstripped their systematization at a modern level, namely the creation of a workable mathematics model process of blast-furnace that could be generalized visitation and forecasting.

Among the methods of cognition of the phenomena of nature mathematical modeling occupies a special place. It allows a deeper insight into the essence of the phenomena better analyze the relationship between processes and on this basis to form forecasts. Fruitful of correct use of mathematical methods in various spheres of scientific knowledge was noted by many outstanding scientists:

Leonardo da Vinci, Immanuel Kant, Max Born, John von Neumann, Norbert Wiener, Jules Henri Poincare, Bertran Russell, Albert Einstein and others.

The use of fine and effective tool for understanding processes mathematical modeling requires first of all a deep understanding of the essence of the studied phenomena and their formalization using successfully selected mathematical apparatus. Found a numerical solution of the tasks and presentation of results should provide the opportunity for focused analysis of not only the output but also intermediate parameters and their relationships. The impossibility to achieve full adequacy of the model to the real process expressed sarcastic remark Norbert Wiener: "the most advanced model of a cat is a cat, but better that he himself." In this regard, the most perfect nature of the model (for example, modular) should provide for the possibility of reconstruction and extensions as testing of the adequacy of the real processes in a wide range of modes. This approach does not always correspond to the possibilities of the application of classical methods for modeling and use of the known methods of the numerical solution. However, the priority of this approach meaningful interpretation of the results dictates the need to find unconventional solutions for modeling and finding numerical solutions in order to preserve the objectivity of the results. Remark A. Einstein on this occasion: "While the mathematical law reflects reality, it is not accurate; as soon as the mathematical law accurate, it does not reflect reality".

In the field of blast furnace processes mathematical modeling takes a big place. The analysis showed that the adequacy of models of real processes depends mainly on the degree of investigated processes (Tovarovskiy, 2009, p.768; Tovarovskiy, 2012; Tovarovskiy, 1987, p.192). Because the adjustment to the real conditions on the parameters of the internal state can only be very approximate (rather qualitatively), its production is carried out on the weekends parameters (coke consumption, performance, parameters of cast iron, slag and furnace gas) that does not allow to give an unequivocal assessment of the adequacy of the model to the real processes. This causes the need to enter empirical coefficients, that are not constant, containing insignificant base of which is not always unambiguous. Despite these difficulties model, which help to better understand the processes and set tasks to further study.

Use of results of experimental researches of blast furnaces, the synthesis of theoretical knowledge about the processes significantly promote the development of a comprehensive model of blast-furnace, the most important results were obtained by Japanese (Blast furnace phenomena and modeling, 1987, p.631) and Russian developers (Knowledge of the processes of blast-furnace smelting, 2006, p.439). The results obtained illustrate the possibility of a wide use of models for the analysis of real technologies and development of new technological solutions. To date, however, such a large-scale analysis for any one model has not been conducted. The reasons for this are not the only difficulties rethink of the whole technology as a whole system, but also the fact that it requires a specific building of models for convenience of handling them in the course of analytical research.

Having set himself the task of overcoming these difficulties, the author of this article began by creating its own model for analytical researches of processes of blast-furnace smelting. In the presence of the models created by other experts, his creation was due; inter alia, necessity compliance with the requirements of consistency of parametric analysis of the performance and processes, including the adequacy of simultaneous reflection on the possibilities of all the processes and indicators on all parameters. Only when using such a model, it is possible to identify a number of regularities, traditionally falling out of attention of researchers and remaining outside the analysis. Specified by the regularities after checking on real objects can serve as a basis for the deepening of the conclusions and developing new technological solutions. Its compliance with the requirements of consistency of parametric analysis of the performance and processes, including the adequacy of simultaneous reflection on the possibilities of all the processes and indicators on all parameters.

Developed in ISI NASU mathematical model of blast-furnace processes is built on the basis of the structural linkage of multiband height, the radius of the blast furnace and General balance of mass and heat. When modeling the blast furnace smelting, the uneven distribution of materials and gases in 12 vertical temperature zones (VTZ) in height and 10 radial of ring zones (RRZ) on the radius of the blast furnace determines the appropriate uneven flow of the processes and polymorphous temperature-concentration, phase and gas-dynamic fields of the furnace volume.

A new approach has opened additional opportunities for the analysis of processes and the emergence of measures to improve efficiency of the smelting, including: identification of the limiting zone and height of the cross section of a furnace; the quantification of the higher heat load of the gas flow in the peripheral zone (for the account of heat losses); the account of gas flows at different horizons of some radial ring zones (RRZ) in the other; assessment of the development of restorative process, in particular the rates of direct recovery of circular cross-sections furnace radius; establish the influence of the distribution of materials for furnace radius on heat loss, as well as the influence of all the technological factors on the consumption of coke into account the changes of heat losses; assessment of the role zone softening and melting (considering the influence of the degree of restitution of iron and ward alkali oxides in the formation of melting modes and the corresponding temperature and concentration fields furnace.

2. STUDYING OF THE INFLUENCE ON THE BF-PROCESSES OF SEPARATE PARAMETERS AND THE COMPLEX OF FACTORS

Analytical studies performed with the use of a multi-zone mathematical model developed by the Institute of Ferrous Metallurgy have made it possible to project the smelting indices that will be obtained in different operating regimes, as well as to discover and better understand certain laws which govern smelting processes and which can be used to improve this technology: direct reduction is minimal at the periphery of the furnace and maximal in the zones with the highest ore burden; radial annular zones (RAZs) characterized by two-stage heat exchange exist over the height of the furnace; the character of heat exchange and coke consumption in all regimes is significantly affected by the heat losses through the furnace wall and depends appreciably on the ore-burden distribution over the radius of the furnace; there are intrsecting gas flows at different levels in the furnace due to changes in the resistance of the different layers of the charge to gas flow and changes in the parameters of the flow as a whole as it is filtered through the stock; the parameters of the softening and melting zones (SMZs) are directly and inversely related to the ore-burden distribution in the top of the furnace, the character of the temperature field that is formed, and the rate of heat removal next to the furnace wall at different levels.

The following was established from an analysis of blast-furnace processes and determination of the effect of the blast (and charge) parameters and the consumption of natural gas (NG), coke-oven gas (CG), and pulverized-coal fuel (PCF) on coke consumption and other smelting indices for different ore-burden distributions in the top (the existing ore-burden distribution (EDB) and uniform ore-burden distributions (UBDs) in intermediate radial annular zones RAZ-2-9-EDB) (I. G. Tovarovskiy, 2009, p.768; I. Tovarovskiy, 2012).

1. An increase in NG consumption decreases the amount of heat available for direct reduction and lowers the rate of heat transfer in the lower region of the furnace while increasing it in the upper region. This elevates the gas and charge isotherms, increases the losses through the top, and causes the softening and melting zones to rise above their base position and expand. Given these circumstances, an increase in NG consumption reduces the differential coke-replacement coefficient (the amount of coke saved with a small increase in NG consumption above the initial value). The coefficient at first decreases smoothly, going from 0.9-1.0 kg/m^3 at NG = 0-50 m^3/ton to 0.8 kg/m^3 at NG = 50-100 m^3/ton. The coefficient is then reduced more rapidly, decreasing by a factor of 1.5-4 at NG > 100 m^3 /ton. The more rapid decrease in the coefficient is due to a sharp rise in top-gas temperature resulting from an increase in the temperature gradient between the temperatures of the gas and the charge in the middle and lower heat-transfer zones, this gradient increase in turn being caused by the substantial reduction that occurs in the heat content of the stock as the degree of direct reduction decreases to r_d < 20%. The same effect is obtained when CG is injected and CG consumption ≈ 2 NG consumption.

With an increase in the consumption of PCF, the temperature field of the furnace changes under the influence of the same tendencies that are seen with the injection of NG and CG. However, the changes are smaller and are not the same for different conditions. The softening and melting zones become narrower and heat losses decrease. The main factor that affects the savings realized in coke consumption when PCF is injected—the replacement of the heat of combustion of coke by the heat of combustion of PCF—elevates the coke replacement equivalent to above 80% and keeps its theoretical value at 0.9-1.0 kg/kg when the consumption of PCF {A^p = 10%, C^p = 82%, content of volatile matter 10%) is increased to 250 kg/ton pig iron. The values actually obtained for the equivalent depend on the completeness of the chemical transformations that take place at the tuyeres.

With an increase in blast temperature T_b in the case of EDB in the high-temperature zones (900°C - $t_{m]}$), more (in terms of mass) gas passes through the more permeable RAZs with a low ore burden than through the less permeable RAZs with a high ore burden. The smaller degree of cooling of the gas in the former RAZs stimulates the gas to flow from those zones into the less-permeable zones through layers of coke and help keep the heat-transfer rate at a level which ensures a reduction in the temperature of the top gas t_t when T_b increases to ~1000°C. In this case, the SMZs in the heavily loaded RAZs are shifted downwards, while the SMZs in the lightly loaded RAZs move upward and decrease somewhat in thickness. The slowing of the decrease in t_t and its subsequent small increase are one of the factors in the reduction in coke conservation (ΔK) and increase in productivity that take place when T_b increases above 1000°C. The range of minimum values of t_t for the variants being considered corresponds to a range of values of theoretical combustion temperature on the order of 2000-2100°C. For the conditions stipulated for each variant, the value of ΔK smoothly decreases by a factor of 2.5-3.5 with an increase in T_b; the largest values of ΔK correspond to the variant in which an air blast is used with NG (0.7-0.2, average 0.40%/10°), while the smallest values of ΔK correspond to the variant in which no NG is used (0.4-0.13, average 0.24%/10°).

An increase in the oxygen content of the blast (%O_2) is accompanied by the formation of additional (high-temperature) gas isotherms in the lower part of the furnace, with most of these isotherms moving upward. The only isotherms that move downward are the low-temperature charge isotherms at the periphery with the EDB and the peripheral and central charge and gas isotherms with UBDs. The downward movement of these isotherms expands the low-temperature region in these zones. That region also undergoes expansion with a low-temperature (200°C) blast. The softening and melting zone is shifted upward into the lightly loaded RAZs and downward into the heavily loaded RAZs (with some increase in the zone's thickness). This tendency weakens with increases in Γ_b and NG consumption; it becomes of little significance at NG > 100 m^3 /ton and negligible with UBDs.

Under the influence of most of the above processes, in most regimes in which $\%O_2$ is increased the value of t_t increases or remains unchanged. This temperature decreases somewhat only in the case of low blast temperatures. Since the unit heat losses do not significantly increase significantly and r_d does not significantly decrease with an increase in the concentration of the reducing agents and shortening of the period of time that the charge is in the furnace, the reduction in the amount of heat supplied to the furnace by the blast when some of the nitrogen is removed from it becomes a more important item in the heat balance. As a result, in contrast to the balance calculations—where it is assumed that r_d and /, both decrease—the increase obtained in productivity with an increase in $\%O_2$ turns out to be smaller (0.9-2.7 versus 1.0-3.0%/%) and the overconsumption of coke turns out to be greater (0.5-1.45 versus 0.1-0.5%/%).

5. The savings in coke that was obtained with the injection of NG and CG turned out to be greater in the case of UBDs (instead of the EDB). The savings was greater due to the increase in the coke replacement equivalent that occurs within the consumption ranges NG > 100 m^3 /ton pig and CG > 200 m^3 /ton pig. The effect of UBDs on the coke replacement equivalent is negligible with the injection of PCF, but with an increase in T_b the savings in coke and increase in productivity are 10-30% (rel.) smaller than with the EDB because the conditions that exist during the smelting operation more closely approach the limiting thermodynamic conditions. When $\%O_2$ increases, coke consumption becomes greater with UBDs than with the EDB.

The above results were used to formulate variants for the systematic use of the parameters of the blast and fuel additives in the blast. Base variants for increasing PCF consumption to 250 kg/ton pig with a blast having an oxygen content of 25% were calculated for the typical operating conditions in two blast furnaces: 5OOO-m^3 BF-9 at Arselor Mittal Krivoy Rog (henceforth referred to as AMKR) and 5500 m^3 BF-5 at the Severstal plant. The feasibility of such PCF use has been demonstrated in practice (Savchuk, & Kurunov, 2000; Danloy, Midnon, & Munnix, et al., 2003). The indicated oxygen content is necessary to more fully gasify the coal at the tuyeres. The base-variant calculations were performed using the highest possible blast temperature (1300 °C) and a CG consumption of 100 m^3/ton pig. In the case of BF-9 at AMKR, calculations were also performed for an additional variant in which the iron content of the charge was increased to 60%. All the calculations were performed with the existing ore-burden distribution and a uniform ore-burden distribution. We also performed calculations for intermediate variants with a PCF consumption of 250 kg/ton pig and actual values for T_b, $\%O_2$, and the other smelting parameters.

It was assumed in the calculations that the ash and sulfur contents of the PCF were no greater than their contents in the coke that was replaced. The physico-mechanical properties of the coke (the indices that characterize cold and hot post-reaction strength) met requirements formulated on the basis of production results that were obtained at the best plants and were generalized (Savchuk & Kurunov, 2000). It was also assumed that the requirements established for minimizing coke consumption are consistent with the metallurgical properties of the iron-ore-based raw materials. This means that those materials can be uniformly distributed in an intermediate annular zone in the top of the furnace (RAZ-2-9) and that nut coke or specially prepared anthracite can be added to the charge mixture to increase the gas permeability of the layers of iron-ore-based materials when the percentage of coke in the stock is low (I. G. Tovarovskiy, 2009, p.768; I. Tovarovskiy, 2012; Yaroshevskii, Afanasieva, Kuzin, & Mishin, 2010).

Special attention was given to the selection of values for the relative ore burden (the specific Ore Burden (OB) relative to the average OB) in RAZ-1 (the axis) and RAZ-10 (the periphery) with the formation of UBDs in RAZ-2-9 (Tovarovskiy, 2009, pp.363-373). It was shown that:

charging the furnace with an ore-burden distribution (OBD) that is close to a UBD in the intermediate zones (RAZ-2-9) is effective only when the charge materials have good physico-mechanical characteristics and it is possible to form axial and peripheral vents whose parameters can be continuously controlled;

the parameters of the axial vent are formed by reducing the OB in the axial and near-axial zones and delivering higher-quality coke to the axis; and

the peripheral vent—an annular channel which is located near the furnace walls and is characterized by high gas permeability—is formed by increasing the porosity of the moving charge materials based on the natural velocity gradients between the layers near the walls; specifically, this vent is formed by regulating the ore burden and the proportions of the charge materials with different permeabilities within this region.

Numerical-analytical studies that were performed showed that as the average ore burden increases, in addition to the formation of a uniform or nearly uniform ore-burden distribution in RAZ-2-9 it is necessary to find the OB values at the axis (RAZ-1) and the periphery

(RAZ-10) that correspond to the properties of the charge and the features of the walls' cooling. The OB for RAZ-10 is chosen with allowance for the increased porosity of the charge due to the natural velocity gradient between the layers near the walls and the rate of the walls' cooling, which is related to the condition of the lining and the cooling system. The parameters that depend on these factors and are to be used to choose the OB at the periphery are determined in the course of adapting the model to the actual smelting operation. For the two blast furnaces being discussed in particular, when a transition is made to OB > 6 tons/ton it was determined that it is best to keep the OB in RAZ-10 lower than the average OB in intermediate zones RAZ-2-9. Otherwise, RAZ-10 will have a retarding effect on the smelting process and lead to a further reduction in coke consumption. On BF-9 at AMKR, the OB in RAZ-10 is 1.05 relative to the mean, with the OB values in RAZ-2-9 going up to 1.1. In the variants in which the absolute value of the OB ≥ 7 tons/ton, the OB in RAZ-10 decreases to 1.0. The most efficient value for the OB in RAZ-10 is even lower (0.9) relative to the mean on BF-5 at Severstal. Here, the OB values in RAZ-2-9 go up to 1.2 and the absolute values go up to 10 tons/ton. This difference can be attributed to the larger heat losses on the furnace at Severstal during the investigated period and to certain aspects of the granulometric parameters of the charge. The granulometric parameters are such as to result in lower charge porosity at the furnace walls than in BF-9 at AMKR (porosity was determined during the adaptation of the model). Figure 1 shows graphs of the OB distribution with the EBD and a UBD.

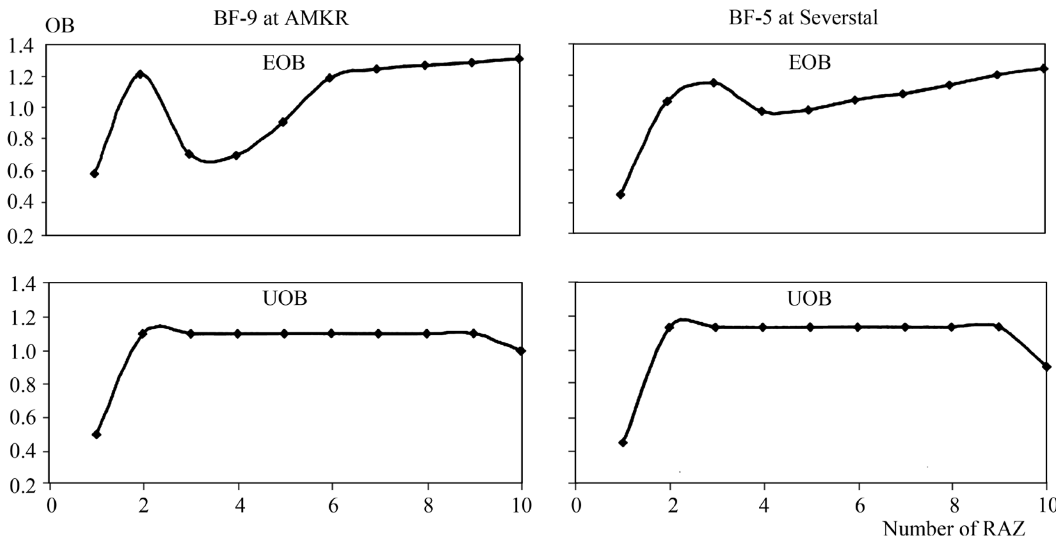

Figure 1
Relative Ore Burdens (OBs) in Radial Annular Sections (RAZs)—Existing Ore Burdens (EOBs) and Uniform Ore Burdens (UOBs)

3. THE MAXIMUM SUBSTITUTION OF COKE AND MINIMIZING ITS CONSUMPTION

Solution of the above problems will help make the use of pulverized-coal fuel in place of coke more effective. The solution is part of a larger system that is being developed to improve smelting by minimizing coke use while keeping furnace productivity high.

Table 1 shows the results obtained from the calculation of several variants in which as much coke as possible was replaced. Figure 2 shows the distribution of the most characteristic smelting parameters in blast furnaces (the numbers t_s, t_m. and $t_{l}$are the temperatures at which softening, melting, and liquefaction begin, respectively, °C).

Coke rates of 304 and 286 kg/ton can be realized with the EBD and a UBD, respectively, on BF-9 at AMKR when the variants used are those in which only 250 kg of PCF per ton of pig iron are injected. The corresponding figures for BF-5 at Severstal are 276 and 257 kg/ton. For blast furnaces on which PCF use is maximal, the coke rate reaches 249-274 kg/ton with PCF consumption in the range 219-260*kg/iron* pig (Savchuk & Kurunov, 2000; Ryzhenkov, Minaev, & Yaroshevskii, et al., 2010).

Changing BF-9 at AMKR and BF-5 at Severstal over to an operating regime with a blast temperature of 1300°C and an additional consumption of CG = 100 m^3/ton would make it possible to optimize the temperature field of the furnaces and use the available reserves for reducing r_d (from 36-38 to 24-25%) while also realizing a significant additional savings in coke (Tovarovskiy, 2012). Taking the increase in the iron content of the charge into account on BF-9 at AMKR, on both furnaces a coke rate of 215-222 kg/ton could be attained with the EDB and a rate of 179-200 kg/ton could be attained with a UBD. Allowing for the substantial positive effect that better-quality coke has on smelting indices, the coke rate that could actually be expected to be obtained is 190-200 kg/ton. These values are close to the minimum possible values of 180-200 kg/ton that were suggested previously (Tovarovskiy, 2009, pp.600-603).

Table 1
Main Theoretical Performance Indices of Blast Furnaces Operated with the Replacement of the Maximum Amount of Coke Possible

Indices	OB distribution variants on BF-9 at the company AMKR							OB distribution variants on BF-5 at Severstal				
	EBD				UBD			EBD			UBD	
	Base	PCF	PCF+CG	+%Fe	PCF	PCF+CG	+%Fe	Base	PCF	PCF+CG	PCF	PCF+CG
Unit productivity, tons/(m^3.day)	1.73	1.74	1.7	1.85	1.82	1.84	1.89	1.76	1.84	1.75	1.9	1.91
Consumption of lumpfuel,kg/ton	505	304	250	215	286	214	200	421	276	222	257	179
Blast temperature,℃	1042	1042	1300	1300	1042	1300	1300	1184	1184	1300	1184	1300
Oxygen content of the blast,%	29.7	25.0	25.0	25.0	25.0	25.0	25.0	24.3	25.0	25.0	25.0	25.0
Consumption of:												
natural gas/coke-oven gas,m^3/ton	80.8/0	0.0/0	0.0/100	0.0/100	0.0/0	0.0/100	0.0/100	106.0/0	0.0/0	0.0/100	0.0/0	0.0/100
PCF,kg/ton	0	250	250	250	250	250	250	0	250	250	250	250
Top-gas tempeature,℃	237	216	297	250	88	133	254	237	146	269	50	70
Content,%												
CO	27.9	23.3	22.7	21.2	23.2	21.4	19.6	21.4	22.2	19.9	20.8	17.7
CO_2	19.4	21.6	19.8	21.4	22.3	21.5	22.7	19.4	24.1	22.9	25.6	25.4
H_2	6.9	2.8	6.8	6.8	2.8	6.9	6.5	7.5	2.7	6.3	2.59	6.2
Iron in the charge	55.17	55.49	55.57	59.94	55.52	55.63	59.96	59.65	59.98	60.08	60.02	60.20
Ore burden,tons/ton	3.54	5.64	6.85	7.47	6.00	8.00	7.88	3.79	5.73	7.13	6.16	8.79
Amount of slag,kg/ton	410	405	402	277	404	401	276	270	261	259	260	255
Wind rate,m^3/ton	1114	1132	1085	982	1061	973	963	1165	1002	1004	951	877
Volume of moist gas,m^3/ton	1815	1679	1716	1574	1594	1569	1535	1831	1522	1597	1451	1428
Theoretical combustion temperature,℃	2233	2193	2110	2060	2177	2056	2051	1999	2277	2086	2263	2017
Amount of tuyere gas,m^3/ton	1631	1504	1568	1436	1412	1426	1413	1689	1340	1467	1276	1306
Direct reduction of F3,%	29.0	34.0	28.1	28.2	36.3	28.0	24.1	25.92	39.01	26.05	37.61	25.31
Degree of use of CO+H_2,%	40.9	48.1	46.6	50.3	49.0	50.2	53.7	47.5	52.1	53.5	55.1	59.0
Heat input,kJ/kg	4807	4743	4800	4327	4451	4299	4245	4443	4421	4419	4203	3852
Heat output,kJ/kg	3640	3747	3596	3317	3791	3577	3217	3170	3484	3162	3447	3115
Heat losses,kJ/kg	455	426	403	395	445	400	412	575	592	577	645	584
Ratio of heat contents of the charge and gas flows	0.82	0.81	0.76	0.76	0.83	0.8	0.77	0.78	0.91	0.82	0.93	0.85
Gas-based smelting rate,m^3/(m^{3}min)	2.17	2.03	2.02	2.03	2.02	2.0	2.01	2.23	1.94	1.94	1.92	1.89

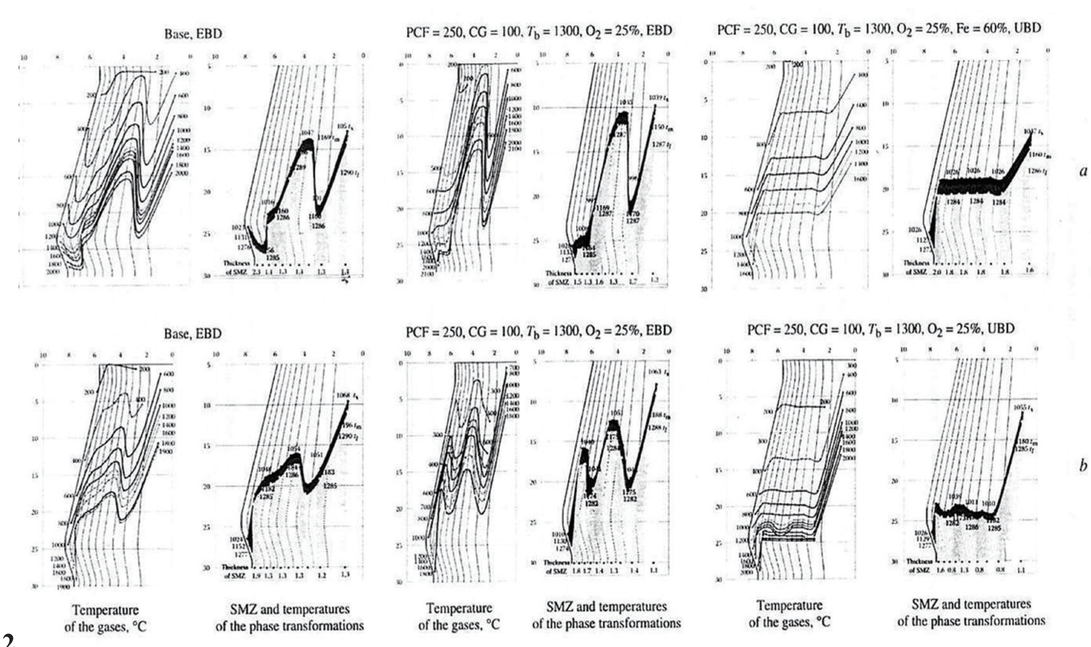

Figure 2
Distribution of Gas Temperature T and the Softening and Melting Zone (SMZ) in BF-9 at the Company AMKR (a) and BF-5 at Severstal(b) with Different Smelting Parameters. Along the horizontal-distance from the furnace axis; along the vertical-ditance from the top(technological datum level), m.

In changing over from the base variant to variants involving the injection of PCF + CG, an increase in T_b to 1300°C with the EBD distorts the temperature field in both furnaces by shifting the isotherms upward in the lightly loaded RAZs. In this case, there is an increase in the number of RAZs with an upper heat-transfer stage that is degenerate or nearly so (see Figs. 2 and 3). The elements of the SMZ are also shifted upward to some extent and the thickness of this zone increases. If necessary, these undesirable effects can be easily controlled by adjusting the consumption of CG and completely eliminating its use when a transition is made to UBDs. The unit heat losses remain almost unchanged on BF-5 at Severstal but decrease by -10 (rel.) % on BF-9 at AMKR. The heat losses decrease in the latter case due to the high temperatures in the tuyere region during the base period.

With the transition to a UBD or a distribution that is similar, the SMZ in RAZ-2-9 is shifted downward while the peripheral part (RAZ-10) remains in the bosh region and the central part (RAZ-1) stays in the middle-top portion of the shaft. In this regime, the upper heat-transfer stage becomes degenerate in all of the RAZs except RAZ-1 and the limiting values for the degree of use of the energy of the gases are reached.

The smelting parameters calculated here and the projected smelting indices can be regarded as being close to the limiting values from the standpoint of minimizing coke use while keeping furnace productivity in the range 1.9-2.0 tons/(m^3 ·day). This is the direction that smelting technology is being taken by the world's leading metallurgical companies, and the same direction can be taken in Russia and Ukraine. However, it cannot be the only approach, and that applies in particular to the emphasis on PCF injection.

These reservations have to do mainly with the more stringent requirements on the quality of the coke and, accordingly, the composition of the coal charge used for coking and the grades of coal available for making PCF. Pulverized-coal fuel cannot be made on an industrial scale due to the shortage of coals of the necessary grades in Russia and Ukraine (Zolotukhin & Andreichikov, 2009; Starovoit, 2010). Another factor—the organizational-technological factor—makes it impossible to effectively employ any smelting technology based on the injection of PCF alone on a small-scale basis. These constraints are related to the quality of the available coke and the grades of coal that can be injected. It is necessary to also inject gaseous additions (NG, CG, etc.).

Thus, realization of the benefits expected from the technology based on PCF injection will first require the solution of a range of problems related to fundamental improvements to the quality of the coke and iron-ore-bearing materials that are used and better control of the processes that take place in a furnace operated with a low coke rate. Although there are known solutions to these problems (Zolotukhin & Andreichikov, 2009; Ryzhenkov, Minaev, & Yaroshevskii, et al., 2010; Starovoit, 2010; Yaroshevskii, Afanasieva, Kuzin, & Mishin, 2010) and the attendant difficulties can be prevented on a limited scale, there are still serious obstacles to success on an industry-wide scale. In particular, there is a shortage of high-quality grades of coal, and that limits the possibilities for implementing this technology (Zolotukhin & Andreichikov, 2009; Starovoit, 2010). The obstacles just referred to—which were not anticipated during the initial period of expansion of PCF injection in Europe and Asia—are not only ongoing problems for Ukraine and Russia but will also soon begin to affect the growth of world metallurgy as the necessary resources become further depleted.

In light of this situation and the increasing shortage of coking coals, coals for making PCF, and quality iron-ore-bearing raw materials (Ryzhenkov, Minaev, & Yaroshevskii, et al., 2010), the "alternative-less prospect" of PCF injection could be leading some metallurgical plants into a dead end. Making sure that this is a sound strategy for the growth of blast-furnace smelting in Russia and Ukraine is particularly important in view of the fact that the arguments made in (Ryzhenkov, Minaev, & Yaroshevskii, et al., 2010) against alternative technologies are completely unconvincing. There, the use of CG was based on a re-examination of the fuel balance of metallurgical plants and the use of products from the gasification of low-grade coals to make up for any shortage of this gas. Meanwhile, many Ukrainian plants have already had success in using specially prepared lump anthracite as a partial replacement for coke (Tovarovskiy, 2012). As regards the injection of hot reducing gases-coal-gasification products (HRG-CGP), the authors of (Ryzhenkov, Minaev, & Yaroshevskii, et al., 2010) are using unreliable information on the losses associated with this technology and its efficiency and are ignoring the sizable losses incurred from the incomplete combustion of PCF and existing limits on the ash and sulfur contents of the coal.

Thus, while expanding the use of PCF-injection technology in the industry and simultaneously improving the metallurgical properties of coke and iron-bearing raw materials are the foundations of technical progress, these efforts should be accompanied by the development of complementary and alternative technologies. This viewpoint is gaining currency among more and more experts, including some who were previously opponents of it (Yaroshevskii, Afanasieva, Kuzin, & Mishin, 2010).

One of the alternatives to the injection of PCF by itself is a flexible technology that combines PCF and CG (or another reducing gas). In the event of a shortage of coals of the grades needed to make PCF (such as low-ash coals), use of the combination technology just alluded to allows the injection of PCF into some blast furnaces at a rate of 100-150 kg/ton pig iron, rather than 200-250 kg/ton pig. In this case, to keep the temperature in the tuyere region at the optimum level and thus keep the temperature field in the furnace optimum as well, it will be necessary to also inject 100-150 m^3 of CG or an equivalent reducing gas (such as standard-grade CG (Tovarovskiy, 2009, p.768)) for each ton of pig iron that is produced. Using this approach, the amount of coke consumed would correspond to a level of PCF injection of 200 kg/ton. If it is impossible (for any reason) to obtain coke having the necessary metallurgical properties, it would be best to reduce the consumption of PCF to zero and increase the consumption of CG to 200-250 m^3/ton. That would make it possible to save enough coke while keeping blast-furnace operations stable.

A technology involving the charging of prepared lump anthracite can be used in different combinations with PCF (including with the complete elimination of PCF, for different reasons). The most illustrative results from the use of such a technology were obtained by the company AMKR during periods when the combine had an adequate supply of anthracite and was able to obtain a quality concentrate (Lyalyuk, Tovarovskii, Demchuk, et al., 2008). With an average monthly consumption of 56-74 kg anthracite/ton pig iron and 70-87 m^3 CG/ton pig, coke consumption reached 427-436 kg/ton pig.

A fundamental solution to the problem of reducing coke consumption to 180-200 kg/ton pig by replacing some coke with low-grade coal might be found by developing a new technology for blast-furnace smelting with the injection of HRG-CGP obtained in special gasifiers—tuyere-side units (located on the blast furnace) and furnace-side units (located in separate housings) (Tovarovskiy, 2009, p.768). Although theoretical interest in solving the above problem has not waned since work on such a technology began during the period 1980-1982 (Tovarovskii, Khomich, & Boyarovskaya, 1982), the interest of potential users of the technology has due to anticipated R&D problems and the complexity of introducing the method on an industrial scale. Nevertheless, the fact that the problem keeps returning for discussion and that some erstwhile opponents have been converted to proponents (Yaroshevskii, Afanasieva, Kuzin, & Mishin, 2010) gives hope that the reality of the situation in regard to coal resources will ultimately be understood along with the urgency of solving the problem by a strategy that was proposed some time ago (Tovarovskiy, 2009, p.768).

CONCLUSION

Prospects for minimizing the consumption of coke in blast furnaces explored through multi-zone mathematical model developed in the Institute of ferrous metallurgy, NAS of Ukraine. We studied the influence of individual parameters and complex of factors. It was found that use of the offered modes will allow cutting coke expenses to 190-200 kg/t of pig-iron on BF-9 AMKR and BF-5 "Severstal". Highly effective technology of pulverized coal injection may not limit the Arsenal of technologies used. Its use should be accompanied by the development of additional and alternative technologies. In particular, attention should be drawn on injecting of coke-oven gas and the products of gasification of low-grade coal, as well as the charging in blast furnaces of specially prepared lump anthracite.

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