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Substitution of Coke and Energy Saving in Blast Furnaces

Part 1. Characteristics of Technology and Uneven Processes—Cognition, Calculation, Forecast

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Abstract

Blast melting is one of the few industrial technologies that preserve the essence and significance by all technical revolutions. This phenomenon exists due to certain properties of the system that ensures exponentially increasing the productivity and linearly lowering the coke rate, that seeks to 200-250 kg/thm. The solution of problems of blast-furnace smelting involves the solution of two analytical tasks: study of the relationship of real parameters and characteristics of the blast melting; forecast of expected parameters and processes on preset parameters of work of the blast melting.

The first task is solved on the basis of balance equations of conservation of mass and energy, the second-based on the method of numerical modeling of processes in radial annular cross-sections along the height of the furnace: multi-zone model of heat-and mass transfer; physico-chemical transformations and mechanics of material and gases. During the numerical and analytical investigation it was shown that the peripheral part of the blast furnace is characterized by the minimum process of direct reduction and also shown that the uniform distribution of burden load provides the minimum fuel consumption.

Key words: Burden; Blast furnace; Heat and material balance; Modeling; Ring radial zones; Vertical temperature zones; Coke rate; Productivity; Natural gas; Blast temperature

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1. CHARACTERISTIC OF THE BLAST-FURNACE SMELTING

Blast melting is one of the few industrial technologies, including processes and unit, to preserve the essence and significance by all technical revolutions. This phenomenon deserves special consideration in terms of its specific and system properties, providing stability in a dynamic industry environment.

Countercurrent principle of technology, carried out in the closed unit shaft type, allows to ensure maximum utilization of the energy input in the base system, and ease the use of the exported products.

The presence at the bottom of the blast furnace carbon extension provides the unique variant, which is typical only for this technology, a feature of combining in one unit three phase state of charge (solid, liquid and softened), located in a counter with gas. The mentioned set of features would seem to be technically impossible, if the blast smelting was invented for anew, but not exist in reality. However, the course of blast-furnace smelting in modern aggregates is characterized by a high resistance during long-continuous operation. Last reached in the result of long evolution development of technology of securing the benefits inherent in shaft counterflow. Unique properties of the blast furnace, that supply a steady flow of processes at high efficiency, were formed in the long course of its evolution.

The advance of the blast furnace practice went at constantly growing rate during the XIV-XIX centuries and did not slow down in the XX century. Among the major achievements in the relevant equipment and processes are the following:

- Intensification and capacity growth of the blowing means and the related increase of the unit volume of the furnaces while their shape, refractories and equipment were upgraded;
- Transition to mineral fuel-coke and continuous improvement of its physico-mechanical properties;

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● Usage of compound sintered iron-containing raw materials with specified properties comprised of a flux component and other additives;

● Blast preheating, its enrichment with oxygen and injection of gaseous, liquid and powdered solid fuel and reducing additives, as well as hot reducing gases;

● Use of up-to-date means of control and methods of smelting processes and equipment operation monitoring.

The XX century advance resulted in an increase in the unit capacity up to 10-12 thousand t/day and fuel rate reduction to 450-490 kg/thm while there are only 280-300 kg/thm of coke in the total fuel volume, the rest being powdered coal or other coke replacement materials.

Data showed that by the end of each century the specific productivity (t/m^3.d) of the best blast furnaces increased exponentially (Figure 1), while the coke rate (kg/thm) lowered almost linearly; such a phenomenon is not quite typical for the development of technical systems and is a proof of the high unused reserves of the blast furnace practice. As regards the coke rate, we see a weak, but characteristic for such systems, form of changes expressed by two conjugated exponents dying down at the final portion.

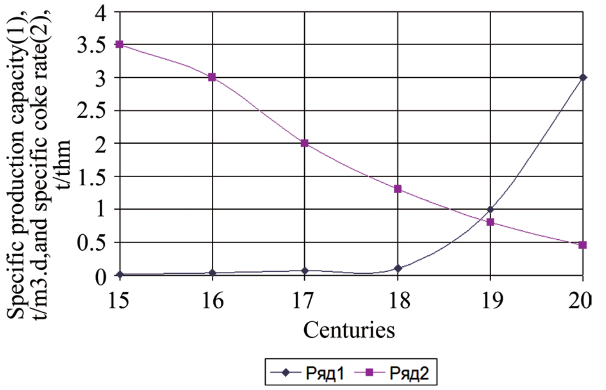

Figure 1
Evolution of the Best Indices in Blast Furnace Smelting

The dying-down curve is distinctly seen for the average indices of the blast furnace practice of the second half of the XX century in the USSR (Figure 2), and is characteristic for other countries. The integral use of the conventional projects known in the art and those being developed to upgrade the blast furnace operation will allow, during the next decade, to reach a specific production capacity of 4 t/m^3.d and coke rate 250 kg/thm (with 200-250 kg/thm pulverized coal injection—PCI) thus approaching the ultimate operation characteristics of a blast furnace within its inherent potential.

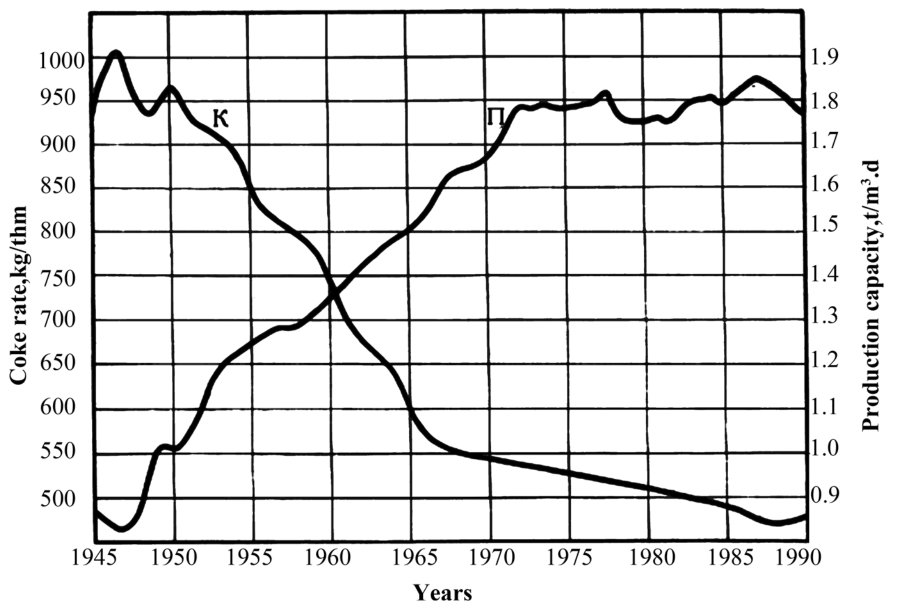

Figure 2
Change of Specific Coke Rate and Blast Furnace Production Capacity in the USSR
K-Coke rate, kg/thm, П-Production capacity, t/m^3.d.

2. METHODICAL RECEPTIONS OF ANALYSIS

The design methods of the analysis are the formalized tool of an understanding of processes in the quantitative form basing on the fundamental laws of the nature. The perfection of this tool is determined by a level of knowledge of the fundamental laws and correctness of their use for the analysis of specificity of investigated processes. The base laws for the closed systems are the laws of preservation of weight and energy, which use at the design analysis of blast furnace smelting assumes a solution of two base tasks: 1) study of interrelations of parameters and characteristics of real blast-furnace smelting; 2) forecasts of expected characteristics of blast-furnace smelting on preset parameters of work.

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The realization of each of the specified tasks is based on a solution of specific problems. In case of the forecast these problems are connected to a correctness of initial assumptions and expedient degree of detailed elaboration of the description of processes (I. G. Tovarovskiy, 2009; I. Tovarovskiy, 2012). In case of the analysis of real technology major value have completeness, accuracy, reliability of the initial information and way of its treatment.

Results of analysis of real technology depend to a great extent on reliability of the initial data, on which he bases. However the last, as a rule, have errors, which sizes are unknown. This not only complicates the analysis, but sometimes deforms its results. Use of design complex parameters and balances including sizes gauged with errors of a different nature and size is especially complicated.

Author of present article in a course of analysis of the characteristics of branch blast-furnaces working has shown that the revealing of disparities of iron, slag-forming and gasified elements balances is a major component of the analysis and has developed a technique of definition of equivalent rejections of parameters at entering the corrections into the initial data and appropriate computer system of the analysis (I. G. Tovarovskiy, 2009; I. Tovarovskiy, 2012). The main role of duration and repeatability accepted for the analysis of the individual periods of work of the furnace is shown, and also method of treatment of results on the ground of the principles of selection and data processing are formulated (I. G. Tovarovskiy, 2009; I. Tovarovskiy, 2012).

The developed system of analysis includes, alongside with gauged initial parameters of processes, also design smelting characteristics: complex parameters of blast regime; iron, slag-forming and gasified elements balances; a heat balance; reducing-thermal and gas dynamics characteristics. The important component of the analysis is the estimation of influence of errors of the initial data on the design characteristics of processes. Without this component the analysis has not that definiteness, which is necessary for reliable conclusions. So, by not estimating an error of definition of any complex parameter in two compared periods of a blast-furnace operation it is impossible to estimate importance of difference of its values in these periods. For such estimation the balances of iron, slag-forming and gasified elements are used. The disparities of these balances are the integrated characteristics of errors of the initial data. The analysis by computer of ponderability of various errors of the account in total value disparities of balances allows to estimate the most probable variants of errors and close to "true" value of design parameters. At comparison of "true" values of parameters in the various periods the "zone of an error", allowing is taken into account and to judge importance of difference of "true" values. So, if at difference of "true" values of a parameter in two periods or for two furnaces "the zones of errors" do not coincide or impose against each other in a small measure, it is possible to consider the specified difference essential. If the imposing of "zones of an error" is large, difference is insignificant. In a number of cases it is necessary to ascertain impossibility to make the certain conclusions of the analysis. Such conclusion is not less valuable, than determined, since allows to avoid erroneous judgements.

The further work in this direction has revealed opportunities of perfection of a technique of use disparitys of balances for an estimation of influence of errors of the initial data on "validity" of design smelting characteristics. The considered below new methodical developments differ from known. On a base of a resulted below analytical solution of a task it is possible to replace used earlier iterative procedure of disparities separation by a more simple and evident way of an estimation of influence of possible account errors on smelting characteristics and to give a solution more suitable kind for the substantial analysis. Besides in considered statement a task of overlapping of balances of iron and slag-forming constituents of burden for the first time is decided.

3. FORECASTS OF EXPECTED CHARACTERISTICS BY MULTI-ZONE MODEL OF BLAST-FURNACE PROCESSES

When choosing a method of forecasting performance and processes of blast-furnace author used the previously performed analysis, which showed (I. G. Tovarovskiy, 2009; I. Tovarovskiy; I. G. Tovarovskiy, 1987, p.192) that the adequacy of models of real processes depends mainly on the degree of investigated processes. 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) and Russian

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developers (Bolshakov & Tovarovskiy, pp. 207-226). 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 the 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, the creation of his 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 served 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, include 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 and 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.

3.1 Zones

The system of discrete material and thermal balances in the radial annular cross-sections for 12 vertical zones is used to describe the heat and mass transfer processes of iron ore reduction in blast furnace. The temperature drop in vertical zones starts from initial temperature to 400°C for the first zone and further with 100°C intervals for other 11 zones with material descend and transformation from the solid to the liquid phase. The temperature of the melt is the bottom boundary of the last zone. The heat and mass transfer processes for specific temperature intervals in each vertical zone are as follows:

- From charging temperature to 400°C—heating and moisture evaporation;
- From 400° to 900°C—material heating and indirect reduction of iron, reduction of easy reduced materials and dissociation of carbonates and hydrates;
- From 900° to 1100°C—heating and a softening of materials, gaseous reduction of iron, carbonates dissociation, Boudourd reaction of CO_2 and carbon and coke de-volatilization;
- From 1100° to 1300°C—heating and fusion of materials, formation of slag, iron gaseous reduction, carbonates dissociation, Boudourd reaction and reduction of hard reduced materials;
- 1300°C—temperature of melt, reduction of the hard reduced materials and melt superheat.

The gas movement in the tuyere zone of blast furnace is three-dimensional. In the bosh the gas flow becomes two-dimensional and in the belly—one-dimensional (Gordon, Maksimov, & Shvydky, 1989; Spirin & Ovchinnikov, 1995). The gas velocity arrows are parallel in the zone of one-dimensional movement in the furnace stack. However, the magnitude of the gas velocity and the gas flow in various areas of the furnace cross-section depends on burden permeability. It is assumed that isobars should be perpendicular to the material streamlines, which is confirmed by the results of the numerous experimental investigations. Two- and three-dimensional gas flow in the area of furnace bosh and belly also can be represented as one-dimensional. In this case the isobar linked the center of the furnace cross-section at the tuyeres level (the horizontal velocity in this point equal to zero) and the point at the bosh wall with the same static pressure should be assumed as the bottom boundary of material column. Above this boundary (isobar) the gas flow through each ring zone depends on the permeability of the burden in this zone.

The typical pressure distribution along the height of blast furnace for the normal furnace operation is very well established in many publications (Zhavoronkov, 1944; Gudenau, Kreibich, & Nomia, 1979, pp.7-13; Bonnenkamp, Engel, Fix, & Grebe, 1983, pp.21-26; Gudenau, Kreibich, & Peters, 1981, pp.13-18; Shturman & Gudenau, 1982, pp.9-14; Peters, Pot, & Peters, 1986, pp.10-20). This quadratic function line could be used to approximate the pressure distribution based on continuously measured blast pressure, top gas pressure and the gas pressure in the middle of the stack. The iteration process allows simultaneous solution of the gas dynamics and heat and mass transfer problems in the volume of blast furnace.

3.2 Heat Distribution

The total volume of the top gas, its temperature, and composition are estimated based on the overall heat and mass balances. The values of the gas flow parameters are assigned for each RRZ based on the previous experience as the first approximation. Knowing the boundary conditions on the furnace top it is possible to estimate heat

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and material balances for the first vertical temperature zone (VTZ) (t^m_{init} 400^0C) for each RRZ. Further the heat and material balances are estimated for VTZ from 2 to 12 (with 100^0C material temperature interval). The heat distribution amongst the separate RRZ is proportional to the amount of materials loaded into this zone and amount of the hot metal produced in this zone.

During calculation of the burden physical enthalpy increment, linear dependence of the specific heat on temperature has been assumed with conditional division into the following components (kg/thm): M—metal-forming; S—slag-forming; C—burden carbon (solid); O—burden oxygen; CD—carbon dioxide of the burden carbonates; Mo —burden moisture. At the upper boundary of the first VTZ (charge level) the burden initial enthalpy, E, is (kJ/thm):

$$E = (0.5 + 0.2\times t_{charge}\times 10^{-3})\times t_{charge}\times M + (0.8 + 0.3\times t_{charge}\times 10^{-3})\times t_{charge}\times S + (1.05 + 0.4\times t_{charge}\times 10^{-3})\times t_{charge}\times C + (0.95 + 0.636\times t_{charge}\times 10^{-3})\times t_{charge}\times O + (0.83 + 0.32\times t_{charge}\times 10^{-3})\times t_{charge}\times CD + (1.19 + 0.175\times t_{charge}\times 10^{-3})\times t_{charge}\times Mo. \quad (1)$$

At the lower boundary of the first VTZ (400ºC) for all the annular cross–sections the enthalpy increment is (superscript– VTZ number, subscript– RRZ number), (kJ/thm):

$$DE^I_i = [0.5\times(400-t_{charge}) + 0.2\times(400^2 - (t_{charge})^2)\times 10^{-3})]\times M + [0.8\times(400-t_{charge}) + 0.3\times(400^2 - (t_{charge})^2)\times 10^{-3})]\times S + [1.05\times(400-t_{charge}) + 0.4\times(400^2 - (t_{charge})^2)\times 10^{-3})]\times C + [0.95\times(400-t_{charge}) + 0.636\times(400^2 - (t_{charge})^2)\times 10^{-3})]\times O + [0.83\times(400-t_{charge}) + 0.32\times(400^2 - (t_{charge})^2)\times 10^{-3})]\times CD + [1.19\times(400-t_{charge}) + 0.175\times(400^2 - (t_{charge})^2)\times 10^{-3})]\times Mo. \quad (2)$$

For other zones simple expressions of a similar form for DE_i^{II}; DE_i^{III} ; …..DE_i^{XII} have been also obtained.

For peripheral RRZ (# 10) the burden enthalpy increment decreases by the value of heat losses through a wall. At known overall magnitude of heat losses Q_{loss} (kJ/m^2 of surface) its distribution amongst zones can be assumed based on the linear dependence of losses on the gas temperature.

The heat of reactions is associated with the temperature ranges of their course. Inside these ranges they are distributed at regular intervals between corresponding temperature zones.

The uniform distribution of the heat of iron direct reduction between VTZ # 7-10 can be conditionally accepted only for the first approximation of the iterative process. However, because of significant contribution of the direct reduction into the overall heat balance, this distribution is estimated in the course of following iterations based on the reduction process kinetics.

3.3 Estimation of Iron Direct Reduction

The following kinetic equation (I. G. Tovarovskiy, 2009; I. Tovarovskiy, 2012) is used to estimate the distribution of heat and the volume of oxygen reduced during direct and indirect reduction amongst VTZ from 2 to 10: $J_R = [(CO^*-CO)\times V_{CO}\times k_{CO}+(H^*-H)\times V_H\times k_H]\times(VFO)^j_i/[(VR)^j_i+(VC)^j_i]$, m^3/(kg×sec), where: ($CO^*$- CO), ($H^*$ H) are the differences of concentrations of carbon monoxide and hydrogen-equilibrium (*) and actual, m^3/m^3, respectively; V_{CO} and V_H—consumption of CO and H_2 respectively per unit of reduced material, m^3/(kg sec); k_{CO}, k_H—constants of CO and H_2 oxidation rate respectively, m^3/(kg sec), determined experimentally for each material with an establishment of their temperature dependences: $k_{CO} = f_{CO}$ (t); $k_H = f_H$ (t); $(VFO)^j_i/[(VR)^j_i + (VC)^j_i]$—relative volume of iron oxides $(VFO)^j_i$ in the burden, m^3/m^3; (VR) and (VC)—bulk volumes of iron bearing materials and coke, respectively (m^3/thm).

The amount of oxygen reduced from the burden by gases in each zone is calculated by the following formula: $O_R = J_R\times t^j_i\times G_{Fe-O}$, m^3/thm, where t^j_i is material residence time in the zone (j-# VTZ, i-# RRZ); G_{Fe-O} is quantity of reduced material (iron oxide), kg/thm. Based on the above parameters, the gas composition (CO–CO_2; H_2–H_2O) is recalculated on the boundary of the following zone.

Gas composition on boundaries of zones and its volume are estimated by adding the oxygen produced by the gaseous reduction to a part of CO and H_2 (with their conversion into CO_2 and H_2O) and adding to the total amount of gas the values of CO_d and CO_L (m^3), formed by oxygen of direct reduction of iron and hard to reduce elements respectively, with relevant gasification of the burden solid carbon C_d and C_L (kg). The calculated balance values, are used for estimation of heat transfer parameters in a specific zone (heat capacity of the burden and gas flows, ratio of heat capacities) and the magnitude of volumetric coefficient of heat transfer $a_v = A\times\sqrt[3]{\Delta P}$ (W/(m$^3\times^0$K)) (A is a constant). The residence time of material in a specific zone is calculated based on the following formula: $t = q / \{a_v\times[(VR)^j_i + (VC)^j_i]\times(T-t)\}$, sec. Special analytical investigation was performed to derive the formula for a_v calculations.

3.4 Analytical Investigation of Heat Transfer Coefficient

Comparing the formulas of Zhavoronkov (1944) for DP: $DP = M\times w^{1,8}\times r^{0,8}\times T/(d^{1,2}\times e^{1,8}\times P)$, Pa/m with formula (Kitayev, Yaroshenko, & Lazarev, 1966; Timofeyev, 1949; Heunert & Willems, 1959, pp.1545-1552; Bogdandi, Engel, 1971; Aerov & Todes, 1968) for volumetric heat transfer coefficient a_v : $a_v = N\times w^{0,6}\times r^{0,6}\times T^{0,3}/(d^{0,4}\times e^{0,6}\times P^{0.3})$, W/(m^3×K), it becomes possible to derive a new formula for a_v: $a_v = A\times\sqrt[3]{\Delta P}$. Here: M, N—constants; w, r, T, P—velocity and density (at normal conditions), temperature and pressure of gas, respectively; d, e—the linear size of voids (analogue to the hydraulic diameter) and voidage of a layer, respectively. Such unconventional form of the formula for heat transfer coefficient is more universal, than known ones, and flexible for fine-tuning of constants and iterative calculations.

4. GAS-DYNAMIC CHARACTERISTICS

The bulk volume of the materials $(VR)^j_i + (VC)^j_i$, (m^3/thm) in a specific zone, incorporated into the calculation procedure, has been defined with respect to the iron–bearing components phase transformation with the temperature increase. The bulk volume of the iron–bearing materials is defined by the expression $(VR)^j_i = R^j_i/(g_R)^j_i$, where R^j_i—consumption, kg/t and $(g_R)^j_i$—bulk density, kg/m^3.

Density of iron-bearing materials total mass: zones 1-8: $g_R{}^j_i$; zones 9,10: $g_R{}^9_i = (g_m + g_R{}^j_i)/2$; $g_R{}^{10}_i = g_m$, whereas melt density $g_m = (M^j_i+S^j_i)/(M^j_i/7800 + S^j_i/2{,}500)$, kg/$m^3$; where: $M^j_i/7{,}800$—volume of hot metal; $S^j_i/2{,}500$—volume of slag, m^3/thm; $g_R{}^j_i$—apparent density, kg/m^3 (3)

Bulk density of iron-bearing materials: zones 1-6 $(g_R)^6_i$; zones 7-10 $(g_R)^7_i = [(g_R)^6_i + g_R{}^j_i]/2$; $(g_R)^8_i = g_R{}^j_i$; $(g_R)^9_i = (g_m + g_R{}^j_i)/2$; $(g_R)^{10}_i = g_m$. (4)

The density of coke total mass in all zones $g_C{}^j_i$ and coke bulk density in all zones $(g_C)^j_i$ are assumed as identical. Based on equations (3) and (4) it is possible to estimate the volume of materials total mass and bulk volume of material in various zones. The linear size of lumps of coke $f_C{}^j_i$ and iron-ore raw materials $f_R{}^j_i$ are estimated by empirical functions of temperature.

The gas velocity under normal conditions could be calculated from the equation of the pressure drop in a packed bed with respect to above specified parameters: $w = [DP \times e^3 \times P\ /\ (M \times r^{0,8} \times `A^{1,2} \times T)]^{0,555}$, $m^3/m^2 \times$sec. The gas volume is used in calculation of the heat balance of each zone. Also it is used for estimation of the material residence time in the zone: $t = q\ /\ \{a_v \times [(VR)^j_i + (VC)^j_i] \times (T-t)\}$, sec and subsequent estimation of the height and the cross-section area of each zone.

Material flow (V_V) and linear velocity (V_L) should be determined prior to estimation of the geometry of each zone: $V_V = [(VR)^j_i + (VC)^j_i] \times P$, m^3/sec; $V_L = V_V / AH$, m/sec, where: P—blast furnace productivity, thm/sec.

Now it is possible to estimate the height of the VTZ—"h^j_i" for each RRZ: $h^j_i = t^j_i \times V_L{}^j_i$ (m) and the distance of top and bottom borders of each VTZ from the stock level as the summation of their heights: $H^j_i = h^j_i + h^j_{i-1} + h^j_{i-2} + \ldots + h^j_1$.

4.1 Boundary Conditions for Material Distribution

The boundary conditions for material distribution on the upper level of material column (upper boundary of RRZ^I_i) are determined as follows:

The iron bearing burden mass $R^I_{åi}$ and its fraction D^I_1, D^I_2, …D^I_{10} ($D^I_1 + D^I_2 + \ldots + D^I_{10} = 1$) are set for each RRZ^I_i.

Initial relative burden distribution (iron bearing materials mass/coke mass) are also assigned for each RRZ^I_i:

$R^I_{1relat.} = D^I_1/d^I_1$; $R^I_{2relat.} = D^I_2/d^I_2$ … ….. $R^I_{10relat.} = D^I_{10}/d^I_{10}$, and $R^I_{1relat.} * R^I_{2relat.} * \ldots * R^I_{10relat.} = 1{,}0$.

The coke mass in each RRZ is calculated based on coke fraction d and $R^I_{irelat.}$: $åd^I_i = 1$.

Such assignment of the raw materials distribution at the furnace top allows to describe all possible variants of materials distribution by coke-less top, two-bell system, rotary charge system (Totem) etc.

4.2 Algorithm Brief Description

The multi-zone balance includes the system of expressions and formulas connected by feed-forward and feedback links. The solution of the multi–zone balance is coordinated with solution of the overall balance under the predictable mode of operation. The predictable mode requires defining of the parameters of the reference period. The reference period allows estimate parameters of operation for each RRZ and VTZ at existing conditions of the blast furnace. By virtue of this, an iterative algorithm with multistage iterative cycles is used to solve the problem.

4.3 Analysis of the Results of Calculations

The average annual operating parameters of blast furnace (BF) with the useful volume of 5,000 m^3 have been used to illustrate the capability of the developed method. The specific production of BF in this period of time was 2 thm/m^3/day (working volume) and the coke rate was 412 kg/thm. BF operated with the following actual distribution of raw materials on the furnace top:

RRZ^I_i	10	9	8	7	6	5	4	3	2	1	Σ
Δ^I_i,%	11.08	10.90	10.64	10.40	10.18	9.91	9.84	10.71	10.13	6.21	100
δ^I_i,%	8.92	9.09	9.36	9.59	9.83	10.13	10.06	9.53	9.89	13.60	100
$R^I_{irelat.} = \Delta^I_i/\delta^I_i$	1.242	1.20	1.14	1.084	1.035	0.98	0.98	1.125	1.024	0.457	1.00

The parabolic and uniform types of material distribution also were used for estimation of BF operating parameters.

Results of calculations with various types of burden distribution on the furnace top showed that coke rate could be decreased by 7.2 kg/thm (~1.75%) in the case of uniform distribution compare to the actual one while

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the parabolic distribution leads to increase in coke consumption by 10.4 kg/thm (~2.5 %). The parabolic distribution of $R^{I}_{irelat.}$ in this case was chosen for "not so opened" peripheral zone ($R^{I}_{10relat.}$ =0.7 from the average value 1). Some "opening" of a peripheral zone ($R^{I}_{10relat.}$ = 0.5 from the average) lead to an additional increase in coke rate by 3.33 kg/thm (~0.78%).

In the case of uniform burden distribution the decrease in coke rate is stipulated by decrease in degree of direct reduction r_d from 28.5-29.1 to 24.6 % and reduction in relative heat losses by 6-6.5 %.

Figure 3 presents the distribution of the gas temperature for the actual and parabolic distribution of raw materials on the furnace top. At uniform burden distribution at the BF top level the height H^{cr} in critical RRZ becomes lower, while the heights of other RRZ increase and become more uniform compare to the actual furnace operation. This positively affects the heat transfer processes in the furnace volume. For example, the degeneration of two-stage heat exchange was observed in RRZ #9 zone in the case of actual burden distribution. At uniform distribution of burden materials the two-stage heat exchange with reserve zone was observed in each RRZ. The uniformity of temperature and concentration fields was improved which led to more stable process (I. G. Tovarovskiy, 2009; I. Tovarovskiy, 2012).

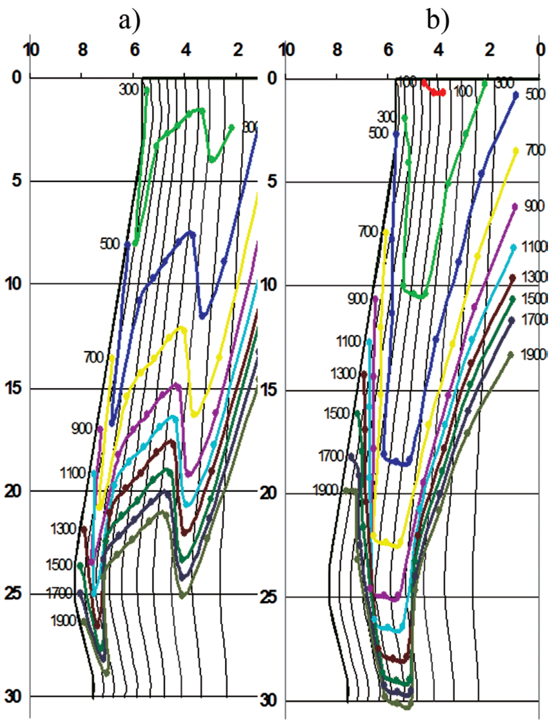

Figure 3
Temperature of Gas in the Blast Furnace by Two Types of Burden Distribution (by Vertical-Distance from the Top, by Horizontal-Distance from the Centre, M) (a) Actual Burden Distribution (b) Parabolic Burden Distribution

In the case of parabolic burden distribution the H^{cr} in critical RRZ increases, while the heights of peripheral and neighboring RRZ zones sharply decrease. As a result the two-stage heat exchange becomes degenerative in VTZ 1-6 at RRZ 5-7. This leads to increase in non-uniformity of temperature and concentration fields and non-stability of blast furnace process.

The results of calculation showed that the minimum extend of direct reduction process takes place in the peripheral part of the furnace. This conclusion developed based on the numerical analysis of the BF process has an experimental confirmation in the work of K. M. Bugaev (Bolshakov, & Tovarovskiy, 2006, pp.190-206). In the case of uniform material distribution on the furnace top, the uniform "r_d" distribution was observed for RRZ 2-9. It allowed obtaining the lower average value of "r_d" by 1.8% compare to the actual material distribution. The decrease in the average "r_d" is even greater compare to parabolic case (by 3.9-4.5%). Decrease in "r_d" was a determining factor in coke rate decrease.

The parabolic material distribution could be attributed to the two-bell charging system. The uniform material distribution on the furnace top characterizes the bell-less top charging system. The overall coke rate decrease in the case of bell-less top compare to the two-bell system is about 3-4%. Improvement in the process stability allows the decrease in a "reserve of technological heat" in the furnace hearth and as a result of this reduction in hot metal silicon and coke rate. Because of this it is reasonable to expect 4-5% reduction in overall coke consumption. The extend of coke rate decrease was experimentally confirmed by results of operation of blast furnace #6 (with bell-less top) and #5 (two-bell system) at Novolipetsk I & S Works (Bolshakov, Tovarovski, & Shutilev, 2005).

5. INFLUENCE OF BURDEN MATERIALS DISTRIBUTION ON THE BLAST-FURNACE PERFORMANCE

The improvement in a blast furnace performance as a result of optimization of metallic burden distribution was the main goal of the current study. All parameters were estimated with respect to the operation of Blast furnace #5 of Severstal and Blast furnace #9 of Mittal Steel Krivoi Rog. The operation of these furnaces was analyzed in three different modes: retrospective, current and perspective. The real mode corresponds with current furnace operation. There is no natural gas and oxygen injection and blast temperature is decreased to 700 °C for the retrospective mode. The perspective mode assumes PCI and coke oven gas injection with the blast temperature of 1200 °C.

Blast furnace performance at each mode of operation was estimated for two distributions of metallic burden load (MBL)—actual and conditionally-uniform (further-"uniform"). The "uniform" distribution can be achieved

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at different MBL on the blast furnace periphery, therefore, the optimization was done based on the minimum total fuel consumption. Other distributions, for example, parabolic, appears to be less effective and characterize mainly two-bell charging system. Analysis of actual furnaces performance confirms the last statement (Bolshakov, Tovarovski, & Shutilev, 2005).

Results of blast furnace operation for different modes are presented in Tables 1 and 2 for blast furnaces #5 of Severstal and BF #9 of Mittal Steel, Ukraine.

Table 1
Parameters of BF #5 of Severstal Operation (Useful Volume 5,500 m^3)

Mode of operation	Retrospective		Current		Prospective	
MBL distribution	Actual	Uniform	Actual	Uniform	Actual	Uniform
Relative to average MBL for periphery	1.24	1.08	1.24	1.15	1.24	1.30
Performance parameters:						
Daily production, thm/day	9,043	9,121	9,799	9,794	9,897	10,123
Specific production (useful volume), t/m^3/day	1.644	1.658	1.782	1.781	1.800	1.841
Coke rate, kg/thm	544.6	538.3	411.6	410.2	290.9	281.6
Air blast rate, Nm^3/min	9,308	9,304	7,678	7,687	7,036	7,021
Blast temperature, °C	700	700	1,184	1,184	1,200	1,200
Oxygen, %	21	21	24.87	24.87	25	25
Natural gas rate, Nm^3/thm	0	0	107.4	107.4	0	0
Coke gas rate, Nm^3/thm	0	0	0	0	150	150
PCI rate, kg/thm					150	150
Top gas temperature, °C	220	216	249	248	241	214
Top gas CO, %	20.27	19.74	21.45	21.21	20.33	19.84
Top gas CO_2, %	20.16	20.60	20.19	20.34	21.58	22.08
Top gas H_2, %	0.48	0.46	7.12	7.06	7.26	7.25
Burden materials rate (kg/thm):						
Sinter	1,032	1,032	1,033	1,033	1,035	1,035
Pellets	488	488	489	489	490	490
Lump ore	50	50	50	50	51	51
Limestone + BOF slag	17+5	17+5	3+5	3+5	0+5	0+5
Fe_{total}, %	59.36	59.37	59.66	59.66	59.94	59.96
MBL, t/t	2.92	2.96	3.84	3.85	5.39	5.57
Hot metal composition, %:						
Si	0.65	0.65	0.65	0.65	0.65	0.65
Mn	0.38	0.38	0.39	0.39	0.39	0.39
S	0.016	0.016	0.016	0.016	0.016	0.016
Slag composition, %:						
SiO_2	35.48	35.47	35.36	35.36	35.23	35.22
Al_2O_3	10.48	10.46	10.07	10.06	9.66	9.63
CaO	37.25	37.24	37.13	37.13	36.99	36.98
MgO	9.92	9.94	10.38	10.38	10.85	10.88
S	0.92	0.92	0.77	0.77	0.62	0.60
Slag amount, kg/thm	321	320	300	300	281	280
Estimated parameters:						
Blast rate, Nm^3/thm	1,482	1,469	1,128	1,130	1,024	999
Oxygen consumption, Nm^3/thm			65	65	60	59
RAFT, °C	2,003	2,003	2,002	2,003	1,995	1,983
Direct reduction of iron oxides,%	36.60	35.43	26.52	25.66	26.19	25.62
Overall gas utilization, %	49.86	51.06	48.48	48.95	51.50	52.69
Overall carbon rate, kg/thm	473	468	358	356	253	245
Overall heat supply, kJ/kg	4,686	4,644	4,350	4,358	4,218	4,110
Overall heat demand, kJ/kg	3,524	3,490	3,190	3,167	3,110	3,090
m	0.772	0.776	0.796	0.796	0.797	0.803
Overall relative gas permeability	21.78	21.68	19.59	19.57	17.27	17.08
Upper relative gas permeability	50.91	50.66	45.74	45.67	40.39	39.88
Lower relative gas permeability	15.49	15.43	13.97	13.96	12.34	12.32
Intensity (coke), kg coke/m^3/day	890.5	887.8	729.3	726.5	520.5	515.4
Intensity (ore), kg ore/m^3/day	2576	2599	2795	2794	2827	2892

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Table 2
Parameters of operation of BF #9 of Mittal Steel, Ukraine (useful volume 5,034 m^3)

Mode of operation	Retrospective		Current		Prospective	
MBL distribution	Actual	Uniform	Actual	Uniform	Actual	Uniform
Relative to average MBL for periphery	1.18	1.05	1.18	1.20	1.18	1.09
Performance parameters:						
Daily production, thm/day	6,197	6,286	6,882	7,040	7,206	7,333
Specific production (useful volume), t/m^3/day	1.231	1.249	1.367	1.398	1.431	1.457
Solid fuel rate, (coke +anthracite) kg/thm	596.9	588	474.3	463.8	326.4	319.4
Air blast rate, Nm^3/min	7,310	7,310	6,263	6,243	5,801	5,797
Blast temperature, °C	700	700	1,103	1,103	1,200	1,200
Oxygen, %	21	21	24.97	24.97	25	25
Natural gas rate, Nm^3/thm	0	0	93.7	93.7	0	0
Coke gas rate, Nm^3/thm	0	0	0	0	150	150
PCI rate, kg/thm	0	0	0	0	150	150
Top gas temperature, °C	238	230	259	249	270	252
Top gas CO, %	22.90	22.40	23.75	23.45	22.20	21.94
Top gas CO_2, %	16.99	17.43	18.05	18.41	19.24	19.52
Top gas H_2, %	0.44	0.43	6.04	6.09	7.14	7.17
Burden materials rate (kg/thm):						
Sinter 1 + Sinter 2 (18)	1,343	1,344	1,345	1,345	1,347	1,347
SevGOK pellets	295	295	295	295	296	296
Ladle slag + limestone	83+22	83+22	83+9	83+8	83	83
Scrap	35	35	35	35	35	35
Fe_{total}, %	55.43	55.44	55.66	55.68	55.93	55.95
MBL, t/t	2.98	3.02	3.73	3.81	5.37	5.49
Hot metal composition, %:						
Si	0.9	0.9	0.9	0.9	0.9	0.9
Mn	0.50	0.50	0.50	0.51	0.51	0.51
S	0.023	0.023	0.023	0.023	0.023	0.023
Slag composition, %:						
SiO_2	38.15	38.16	38.33	38.35	38.57	38.58
Al_2O_3	3.82	3.79	3.29	3.24	2.59	2.55
CaO	46.54	46.56	46.76	46.78	47.05	47.07
MgO	6.14	6.15	6.34	6.36	6.61	6.62
S	1.87	1.85	1.55	1.52	1.11	1.09
Slag amount, kg/thm	384	383	367	366	347	346
Estimated parameters:						
Blast rate, Nm^3/thm	1,699	1,675	1,310	1,277	1,159	1,138
Oxygen consumption, Nm^3/thm			76.7	74.8	68.4	67.2
RAFT, °C	2,008	2,008	2,078	2,068	2,057	2,049
Direct reduction of iron oxides, %	38.8	37.6	27.9	27.9	25.9	25.7
Overall gas utilization, %	42.60	43.76	43.18	43.97	46.45	47.09
Overall carbon rate, kg/thm	524	516	416	407	286	280
Overall heat supply, kJ/kg	5,437	5,362	5,111	4,972	4,866	4,776
Overall heat demand, kJ/kg	4,025	3,991	3,677	3,668	3,530	3,520
m	0.729	0.734	0.779	0.786	0.779	0.783
Overall relative gas permeability	15.9	15.9	15.1	15.0	13.8	13.7
Upper relative gas permeability	36.9	36.7	34.0	33.9	31.4	31.2
Lower relative gas permeability	11.2	11.2	10.6	10.6	9.7	9.7
Intensity (coke), kg coke/m^3/day	727	726	641	642	462	460
Intensity (ore), kg ore/m^3/day	2,139	2,170	2,378	2,433	2,493	2,538

The following conclusions could be made from the results of blast furnace performance investigation:

- The uniform distribution of MBL provides the minimum fuel consumption
- It is necessary to increase MBL on the periphery of the furnace with decrease in coke rate to achieve the minimum coke consumption.
- It is also necessary to increase the average MBL value using such technological measures as PCI, injection of coke oven gas, increase in blast temperature etc.

The major factors in the reduction of the coke rate with uniform distribution of MBL are as follows:

- Improvement in heat transfer which finally leads to decrease in temperature of the top gas

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- Reduction in heat demand for direct reduction due to decrease its fraction and increase in a degree of gas utilization
- Reduction in heat losses through the walls because of increase of MBL at periphery of the blast furnace and an increase in the furnace productivity

The improvement in the uniformity of the radial temperature and gas distribution with the transition to the uniform MBL distribution reduces the number of RRZ with degenerative upper heat exchange zone. It is well known that the degenerative heat exchange increases the total fuel rate because of the increase in heat demand.

The results of investigation showed the direction in improvement of MBL distribution: uniform MBL distribution in RRZ 2-9 at maximum possible MBL at periphery. It is also important to maintain the axial gas flow, which mainly depends on quality of coke (especially coke charged into the axial part of the furnace cross-section), quality of metallic burden, parameters of blast and other technological factors.

The comparison of Severstal and Mittal Steel, Ukraine blast furnaces performance with three types of mode of operation (retrospective, current and perspective) shows the following:

- The extend in the coke rate decrease during the transition from the current mode of operation to the perspective one for Severstal blast furnace is lower—120,7 kg/thm compare to 148 kg/thm for Mittal Steel, Ukraine blast furnace
- The extend in the coke rate increase during the transition from the current mode of operation to the retrospective one is higher for Severstal blast furnace—133 kg/thm versus 122.6 kg/thm for Mittal Steel, Ukraine blast furnace.

Such difference reflects the fact that operation of Severstal blast furnace is much closer to the limiting conditions compare to operation of Mittal Steel, Ukraine blast furnace.

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