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THE PHILOSOPHY OF BLAST FURNACE MELTING AND THE TECHNOLOGY OF IRONMAKING

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The book contains a wide circle of questions of metallurgy of pig-iron that considered in the context of cognition of the blast smelting, her modern state and evolution. The analysis of processes, parameters, and indexes of smelting and modern achievements of blast furnace production also methodical developments of the analysis of the real production, modeling of blast furnace processes and prognosis of the expected prospects are given in the book.

The book examines the problem of knowledge of the blast-furnace processes on the basis of their modeling and analysis. With using the developed in the Iron and Steel Institute of NASU multi-zone mathematical model it is possible to estimate the expected performance under various technological regimes, and to identify and clarify some of the patterns of processes that can be used to improve the blast furnace technology.

The book is intended for the wide circle of specialists of ferrous metallurgy and contiguous with her areas, and also students of higher educational establishment's metallurgical, economic and administrative profiles.

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CONTENT

INTRODUCTION

One of the forms of social consciousness – philosophy is the science of the most General laws of development of nature, society and thinking, and in relation to a particular subject reflects methodological principles of formation and a meaningful framework for its development.

By the early nineteenth century advances in science have allowed, and the practical needs of the industry claimed to direct the efforts of engineers and scientists focused on the cognition and the development of the theory of the blast smelting as a basis for technical progress [1-5]. The subsequent period of broad implementation of this process showed the necessity of its generalization, which at this stage is performed at the Iron and Steel Institute National Academy of Science of Ukraine in the form of successively held international symposia with the participation of leading experts and a wide discussion of the problems [6, 7].

Problems cognition processes and developing technology for blast-furnace production are considered in detail by the participants of the Symposium on directions and generalized in the present work, which also includes the problems of systematic analysis, principles of operation, modeling, and forecasting. The said complex, as described below, the problems of obtaining new knowledge are designated as "the philosophy of the blast smelting".

The problems of normalization of fuel resources in blast furnace based on a systematic approach

1. COGNITION OF PROCESSES AND THE FORMATION OF TECHNOLOGY BLAST SMELTING

1.1. Systemic character and principles of functioning of blast furnace smelting processes

The traditional approach to the analysis of the blast furnace based on detailed investigation of individual phenomena (heat and mass transfer. etc.) and then use the discovered patterns to determine the possible and desirable trends in the development of processes and management. This approach is fruitful, however, not quite sufficient for a complete understanding of the process with a view to their improvement. This is because the blast smelting in General is not the simple aggregate of individual phenomena, but a complex function of their relationships, the nature of which the events themselves and includes properties that are not inherent in particular phenomena. These peculiarities of the processes of the blast furnace allow to characterize it as a large system in modern understanding, including new concepts, including [8]:

Integrative qualities - the qualities of the system as a whole, but not peculiar to its elements separately. The properties of the system, although dependent on properties of its elements, but not completely determined by them.

In view of the above in the study of metallurgical technologies and their development requires the use of the ideology of the system approach as methodological basis of study of large systems.

Problems of cognition the actual process of the blast smelting is still not intended as an independent and generated by the accumulation of empirical material, and a certain degree of its comprehension. At this stage there was a need of understanding the process to make it more dynamic. The basis of understanding of the process of cognition can be the analysis of its evolution (according to G.W.F.Hegel) and considering some General principles in blast smelting.

The first of them was formulated by M. A. Pavlov [2], summarizing the position expressed earlier by R. Okerman [3], in relation to the process of heat absorption. In our broader interpretation with justification for all other processes it is expressed as the principle of attenuation [4]: the Maximum effect of the application of each measures to improve the blast furnace is achieved under conditions opposite to those leading on this event. It is complemented by the principle of combination: the most effective combination of activities that affect essential processes in the furnace in opposite directions.

Considered two principles cover the blast melting as a simple collection of phenomena, but do not consider unity as a large system in which relationships between elements are not less important than the elements themselves, and the system includes properties that are not inherent in its individual elements. The improvement of such systems, the number of complex parameters closer to the ultimate state regardless of influencing factors. In blast smelting, in particular, decreases the residence time of the materials in the furnace, reduces the amount of gases per unit of materials, increasing the intensity of filtration of the melt through the nozzle of the coke, thereby reducing the stability of the course of processes and complicates the management. Formally, this translates into reducing the entropy of the system. A systematic approach to blast furnace smelting allows us to formulate the principle of limiting regimes:

With the improvement of technology the blast furnace and its approach to some limiting regime, the effectiveness of the entire set of measures for its further improvement is reduced.

In addition to the above, blast smelting has a number of system properties which are designated below in General form:

Any energy imbalance that occurs in the input or intermediate stages of melting stretched in time and does not output the final state of the specified limits (ADAPTABILITY).

Because of the uneven distribution of the medium and its properties in the unit volume of each mode contains components not relevant average parameters and deforming over time average parameters and indicators of melting by the accumulation of new properties, stimulating the spontaneous shift of the status of processes in other area and require an adjustment mode to achieve the specified performance (SPONTANEOUS SHIFTS).

Each step of cognition (Cl, C2, C3...) is a precondition of development (Dl, D2, D3...), and the next step of development - an incentive to further knowledge (D2, D3,...). The result is a multivariable dynamic system (MDS).

Thus, at the present stage of study of the blast furnace we go from knowledge of individual processes to the knowledge of its system properties. This will allow not only a better understanding of the regularities of the system "blast smelting", but to create the preconditions for forecasting the further development of technology. In this way, the importance becomes a method of cognition.

1.2. Methods of cognition the processes of blast smelting (Bs)

By the mid-19th century the study of the processes of the BM acquired an independent value. In the subsequent half century on the basis of use of achievements of fundamental Sciences and numerous experimental studies in laboratories and blast furnaces created a system of knowledge suitable for practical use, the significance of which received a vivid description of L. Boltzmann: "there is Nothing more practical than a good theory".

By the end of the twentieth century has accumulated a large amount of knowledge, some of which are repeats of each other, while others are contrary to the results of similar studies. The explanation of the results with the same positions all the more difficult. This is due to the fact, that the accumulation of knowledge was ahead of their systematization at the present level, namely the creation of a workable mathematical model of the blast furnace process, on the basis of which possible generalization and prediction.

Among the methods of cognition of natural phenomena mathematical modeling occupies a special place. It allows you to penetrate deeper into the essence of phenomena, to better understand the relationship of processes and on this basis to form forecasts. The fruitfulness of the correct use of mathematical methods in various fields of scientific knowledge was noted by many outstanding scientists: Leonardo da Vinci, I. Kant, M. Bourne, George von Neumann.

Thus the correct use of mathematical methods is complicated by the need for a deep understanding of the subject essence of the phenomena and the intricacies of the mathematical apparatus and characteristics of system analysis processes. Since this approach is not available to many researchers, a number of eminent scientists have considered the problem of skepticism, and sometimes with irony:

Since then, as for the theory of relativity began math, I already did more, don't understand... There is an amazing opportunity to master the subject mathematically, not understanding the merits of the case. A. Einstein.

The most perfect model of a cat is a cat, but better - himself. N. Wiener.

Thus, the use of subtle and effective means of cognition of the processes of mathematical modeling requires a deep understanding of the essence of the phenomena and their formalization with the use of well-chosen mathematical apparatus. Numerical solution of the problem and the presentation of results should enable a substantive analysis of not only output but also the intermediate parameters and their relationships. Given the impossibility of achieving the complete adequacy of the model to the real process (see, e.g., comment N. Wiener above), the nature of model construction (e.g., modular) needs to be adjustment and additions as the verification of the adequacy of the real processes in a wide range of modes. This approach does not always meet the possibility of applying classical methods of modeling and the use of known methods of numerical solution. However, the priority of this approach is the meaningful interpretation of the results dictates the need to find innovative solutions in terms of modeling and finding numerical results in order to preserve the objectivity of the results (see A. Einstein).

In blast melting process the adequacy of models of real processes depends mainly on the degree of scrutiny processes.

Using the results of experimental researches of blast furnaces in the synthesis of theoretical knowledge about the processes significantly promote the development of a comprehensive model of the blast furnace, and the most significant results obtained by the Japanese and Russian developers. The results illustrate the possibility of wide use of models for the analysis of real technologies and development of new technological solutions. To date, however, such a large-scale analysis of any model are not carried out. The reasons for this are due not only to the difficulties of rethinking technology as a whole system, but also those that require a specific construction of models for ease of handling them in the course of analytical studies.

Setting himself the task of overcoming these difficulties, the developers of Iron and Steel Institute NAS of Ukraine started with creating your own model for analytical researches of processes the blast furnace. Of the models previously created by other professionals, the creation of his was due, among other things, the need to match the requirements of consistency of parametric analysis of performance processes, including the adequacy of simultaneous reflection on the possibilities of all the processes and indicators on all parameters. Only when using this model it is possible to identify certain regularities traditionally drop out of attention of researchers remain outside the analysis. The above regularities after checking on real objects can serve a basis for deepening of insights and development of new technological solutions.

Developed in the Iron and Steel Institute NAS of Ukraine mathematical model is characterized in that on the basis of the structural linkage of multiband height and radius of the blast furnace and General balance of mass and heat increased the predictive power of the model, including by establishing new quantitative relationships of the processes and identifying the influence of the uneven distribution of materials for furnace radius on the performance of melting. In addition to the quantitative clarification of the relations of the initial parameters and final results (coke consumption, productivity), revealed the internal communication processes in the furnace volume (including some new) that affect the character of the smelting regimes and the final results. Along with the balance factor of coke saving in determining the basic amount of decrease of heat consumption, the calculations take into account and evaluated a significant influence on the coke consumption of the nature of heat and mass transfer, phase transformations, gas-mechanic and distribution of materials and gases in a furnace, connected direct and feedback with the coke consumption.

The new approach opened up additional possibilities for the analysis of processes and generation of measures to improve the efficiency of the smelting, including the limiting detection zone height and the cross section of the furnace.

1.3. Forecast of indicators and assessment

Using the developed model based on the performance indicators of BF № 9 OJSC "AMKR" one of the characteristic periods performed a comprehensive analytical study of blast furnace processes, including multivariate calculations for processes with variation in a wide range of the actual values of the parameters of the charge injection and distribution of materials o/n the furnace top. The latter is illustrated in Figure 1.1 the relative values of ore loads (OL relative to the average) radius of the furnace. Shows the distribution of three types of OL in two variants:

1) if the original terms of the English: cone cool - CC, the smooth flume SF, flume uniform FU.
2) if the original terms of the Russian: ККр=CC ЛП$_Л$=SF ЛР=FU

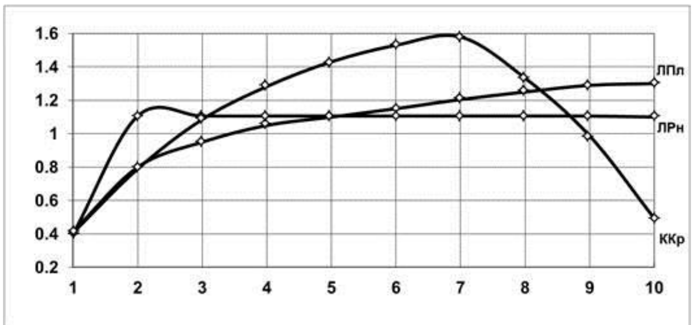

Figure 1.1. Relative load ore RN on the top (ore load vertically) in the vertical annular zone number 1-10 (horizontal) for three variants of the ore load distributions: ККр=CC, ЛПл=SF, ЛРн=FU

Study on the influence of the input parameters of melting on the formation of temperature-concentration and phase fields of BF showed significant quantitative differences for different parameters: the most powerful, along with the distribution of materials was the influence of preliminary metallization of the charge, consumption of natural (coke oven) gas, oxygen and blast temperature; other parameters influence is weaker. The studies revealed some new regularities of the processes of melting: 1) a variety of schemes of heat transfer along the height of the radial zones, up to the degeneracy of the upper level heat transfer or transformation temperature field BF in the direction of the scheme inherent in the cupola furnace; 2) a minimum radius, the development of direct reduction of iron from the periphery; 3) the flow of gases in the radial direction at different horizons; 4) a complex system of forward and backward linkages of the parameters of the zone of softening and melting (SMZ) with a set of input, intermediate and output parameters; 5) same for heat removal from the walls of the furnace.

Analysis of the modes of the BF showed:

The uneven distribution of materials and gases in 12 vertical temperature zones (VTZ) in height and 10 radial annual zones (RAZ) radius of the blast furnace determines the corresponding the unevenness of the processes and polymorphism of temperature-concentration phase and gas-dynamic fields in the furnace volume.

At the same time for RAZ with high actual ore load is characterized by degeneration of the upper stage of heat transfer and the increased development of direct reduction, leading to a shortage of heat in high temperature VTZ and the corresponding increase in total demand of heat and the consumption of coke. The redistribution of the OL - radius, weakens this process and the concentration field is influenced by processes in the zone of softening and melting (SMZ) gas flow "wraps around" the SMZ through the "vents".

The backflow furnace gas is a single coherent system of movement of the batch and gas in conjunction with the products of their interaction, phase transitions and energy exchange. The movement of gas occurs not only vertically. The most complex trajectories have the axial and peripheral flows, particularly in the area of "wrapping" the SMZ (Figure 1.2). In RAZ-10 (periphery) is observed at 20-25 m, rRAZ-1 (axis) is 7-10 m. Above the zone of flow is the outflow of gas from the periphery and axis in the intermediate RAZ-2-9 reduction of amount of gas in the RAZ-1 in 1.5-2 times (up to 0.06 m^3/m^3) and the change in the composition, including the expense of taking away oxygen from the charge and transporting in vertical and horizontal directions. Contours of the temperature difference (T-t) in combination with gas isotherms (Figure 1.3) illustrate the temperature field of the BF in conjunction with these factors, and the inflection of the curves at the minimum value of (T-t) denotes the position of the boundaries of the zones of heat transfer for each of the 10 RAZ (from 5 to 20 m). The concentration field is influenced by the amount taken from the batch of oxygen and form mirrors that of the temperature field (Figure 1.3).

The maximum development of direct reduction often takes place in the RAZ-1 (Central) and 30-50% under the average for furnace 20-40%; the minimum is achieved in RAZ-10 (peripheral) is 3-15%. In the transition to the uniform distribution of the OL of the leveling values of the degree of direct reduction in the -2-9 and most often a decrease in the degree of direct reduction in RAZ-1 and 10..

Organically inherent in the cone of the boot devices (cbd) parabolic distribution of ore loads characterized by high values of OL to 2 – 3 RAZ intermediate and significantly different from the distribution of OL when loading a bell-less device (bld), providing a more uniform distribution of OL. This allowed on the basis of the approach is first to estimate by calculation (using the model) the expected reduction in coke consumption when using the bld insted cbd.

Radical process changes occur with increasing degree of preliminary metallization of the charge reduces the heat load on the direct reduction of iron and, accordingly, decreases the specific heat igratio of the mixture and gas, as well as the intensity of heat transfer in the lower zone (Figure 1.4). This increases the need for heating the products of smelting height of the bottom step of heat exchange and consequently reduced the height of the upper if you increase the minimal height difference, and temperature of the charge and gas. The result is gas isotherms move upwards, increasing the losses through the furnace top, and the area of softening and melting points will be above the base position and thickens (Figure 1.4). Under the influence of these phenomena the main balance factor of coke saving from the use of pre-metallized charge cannot be implemented adequately if the degree of metallization of more than 20% because the heat and mass transfer processes, phase transformations and gas-dynamic develop in the direction of limiting the effectiveness of the implementation of this technology (Figure 1.4)

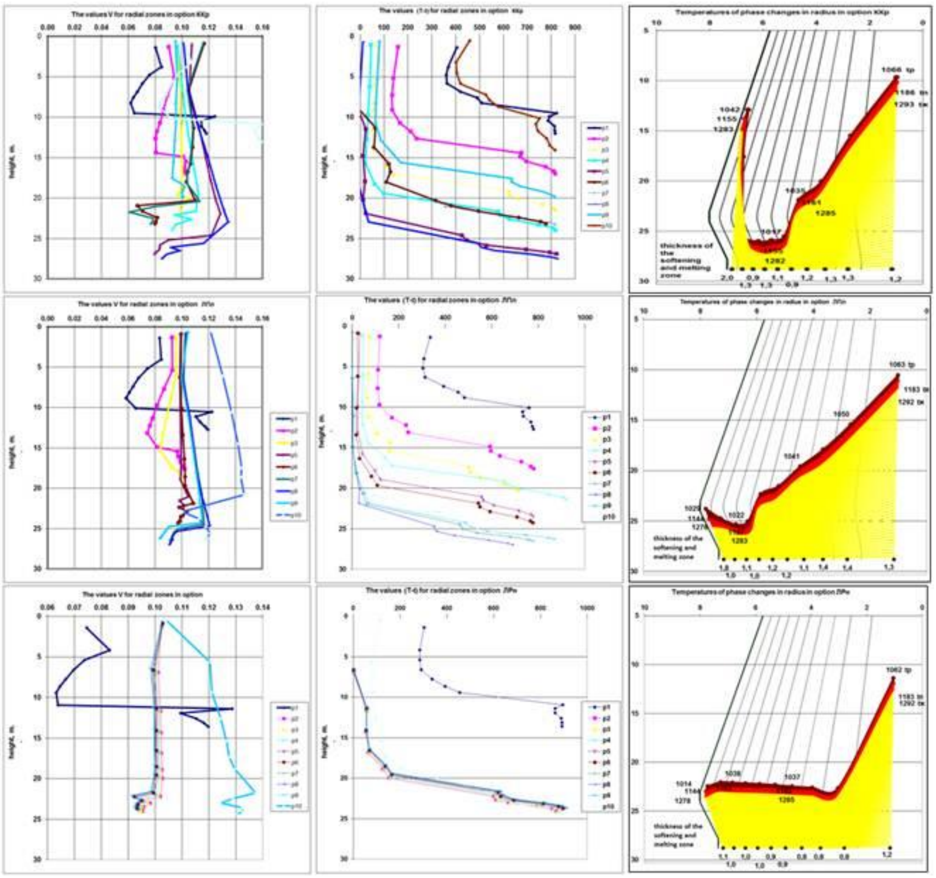

Figure 1.2. The amount of gas in the radial annular zones RAZ-1-10 (V- the proportion relative to the total – graphics on the left); the temperature difference between the gas and burden (T-t) - in central; parameters of softening and melting zone (ZSM - on right) for the three variants of distribution of the ore load on the top: ККр (the first row of graphs), ЛПл (second row), ЛРн (third row); parameters softening and melting zone on the radius of the furnace at different heights (the vertical distance from the top, m) for three variants of the relative distribution of the ore load (vertically) in RAZ-1-10 (from the horizontal axis, m). $t_р$, $t_{пл}$, $t_ж$ – temperatures softening point (brown), melting (red) and liquefaction (yellow), respectively

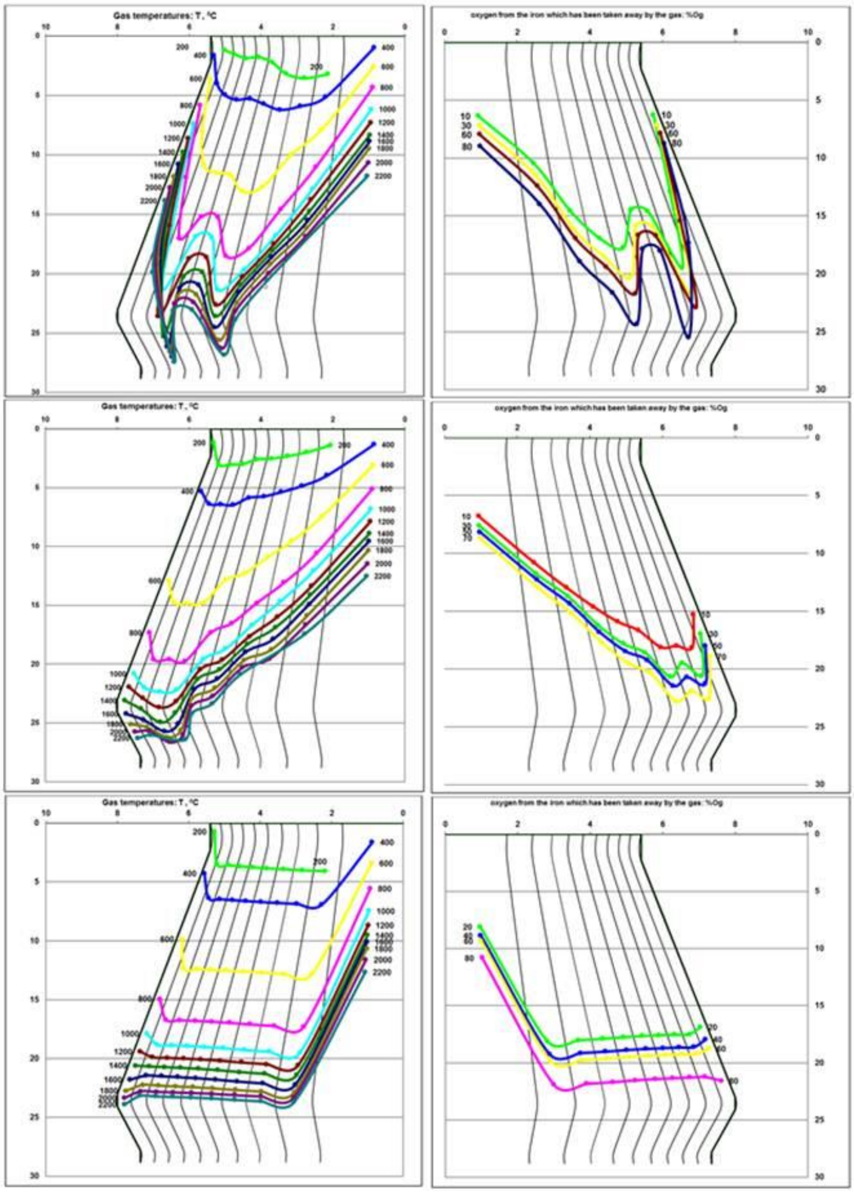

Figure 1.3. The isotherms of gas and contour lines of the amount taken away oxygen gas from the burden into working space of the blast furnace. Horizontal - the distance from the axis, m Vertical - the distance from the furnace top

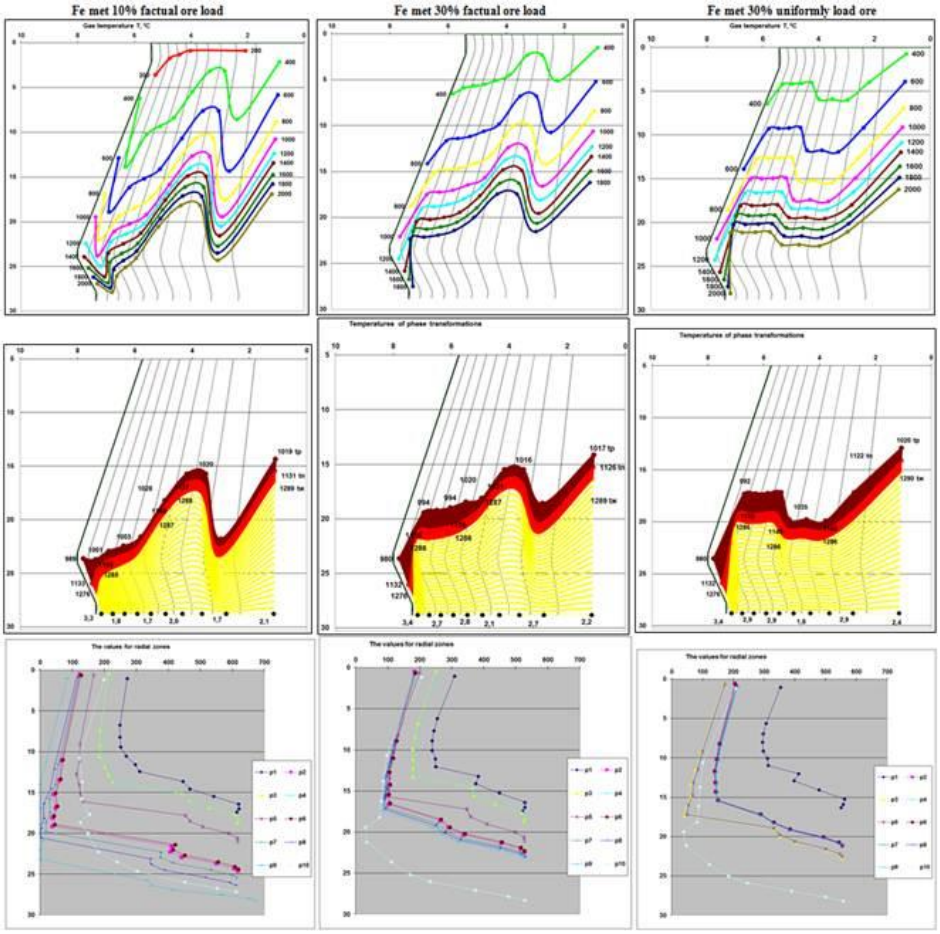

Figure 1.4. The isotherms of gas (top graphics); softening and melting zone (average graphics); the difference between the gas temperature and the burden T-t (bottom graphics) in the volume of BF-9 "ArcelorMittal Krivoy Rog" (RAZ p1-p10) with varying degrees of pre-metallization of burden. Vertical: the distance from the top of the furnace, m. Horizontal: distance from the center of the furnace, m (upper and middle graphs); the difference between the gas temperature and burden (lower graph)

The most important characteristic of the flow rate of natural gas (NG): reduces the heat load on the direct reduction of iron and, accordingly, decreases the specific heat ratio of the mixture and gas, as well as the intensity of heat transfer in the area while increasing it in the upper area (Figure 1.5). As a result, the increase in the consumption of NG to 100 m^3/t cog. the equivalent of coke substitution (ECS) is about 0.8–0.9 kg/m^3, with a further increase in the flow of GHGs and the reduction degree of direct reduced to rd<20% there is a sharp increase of the temperature of the flue gas, leading to a reduction ECS in 1.5–4 times.

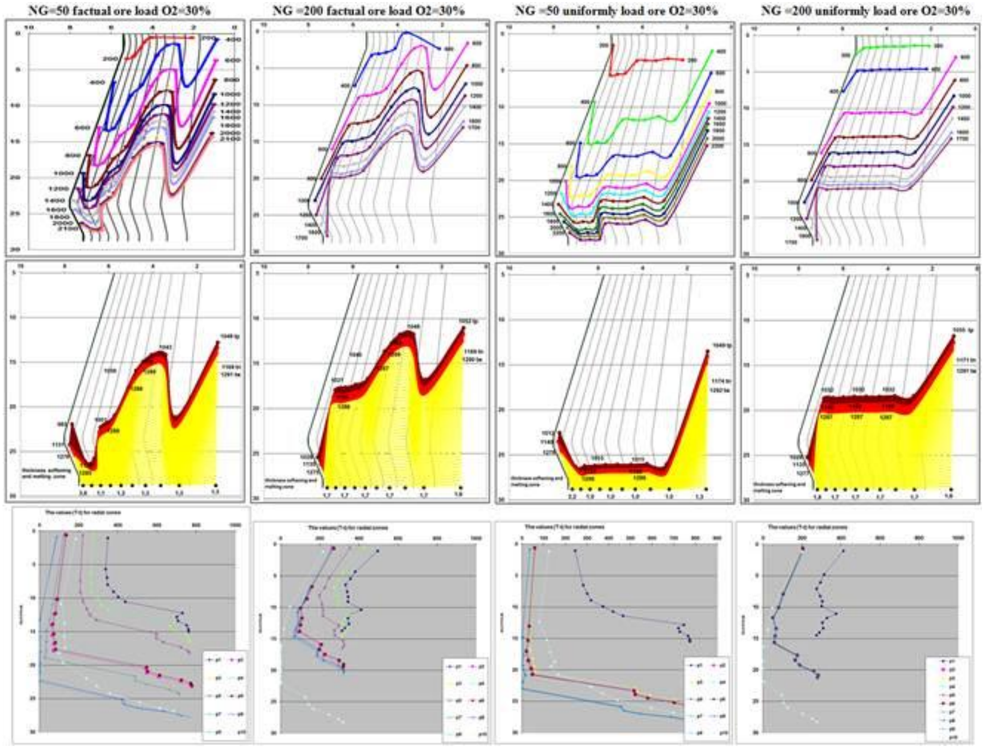

Figure 1.5. - The isotherms of gas (top graphics); softening and melting zone (average graphics); the difference between the gas temperature and the burden T-t (bottom graphics) in the volume of BF-9 "ArcelorMittal Krivoy Rog" (RAZ p1-p10) at various flow rates of natural gas and blast content in 30% O_2. Vertical: the distance from the top of the furnace, m. Horizontal: distance from the center of the furnace, m (upper and middle graphs); temperature difference between gas and the burden T-t (lower graphs)

The General direction of the deformation of the temperature field of the gas flow with increasing flow rate PG is the same as deformation using a pre-metallized charge, where there is a gradual transformation inherent in the blast furnace process diagram of heat transfer in the direction of the scheme inherent in the cupola (see above).

Based on the performed parametric analysis the favorable conditions for the comprehensive use of the best melting parameters and performed analytical research of indicators and processes blast furnace in terms of maximum reduction of coke consumption due to its replacement of coal (250 kg/t) and coke oven gas (100 m^3/t) with the increase of T of blast up to 1300°C and concentration of oxygen of 25% when the content of iron in fluxed fully charge up to 60% and required improvement of the metallurgical properties of coke and raw materials and also optimizing the distribution of materials on the furnace top. Calculations the possibility of reducing coke consumption in this mode up to 190÷200 kg/t cog. Taking into account the implementation of rational distribution of ore loads on the furnace top in this mode, there is a tendency to degeneration of the upper stage of heat transfer in RAZ-2-10, which is amenable to inhibition by addition of coke oven gas. They meet the limit values of degrees of use of energy gases. SMZ moves down while maintaining the peripheral part RAZ -10) in the region of shoulders and Central (RAZ-1) – in the middle-top of shaft.

Highly efficient technology of PCI may not be the only in the industry in connection with the shortage of high-grade coals and dynamic market conditions. Its expansion must be accompanied by the development of complementary and alternative technologies, in particular combination with the injection of coke-oven gas, products of gasification of low-grade coals of wide application, etc., as well as a download of a specially prepared lump anthracite. The fundamental solution to the problem of reducing coke consumption to 180÷200 kg/t of pig iron using its replacement of low-grade coals can be obtained on the basis of the development of new technology the blast furnace with injection of hot reducing gases – products of gasification of coals [9,10] obtained in special gasifiers two types: 1) on each tuyere device blast furnace, 2) in a separate Assembly outside of the furnace.

Identification is considered and other possible patterns based on processes blast furnace in the form of a polymorphic complex temperature-concentration phase and gas-dynamic fields in the volume BF, is discretized by 120 local volumes that are linked by a single system of material and heat balance identifying the local limiting volume. Analysis of processes on this basis avoids at least the system errors inherent in prior approaches. The prediction of the efficiency of using pre-metallized raw material with the help of the model, which postulated a value of the temperature difference between gas and burden on the border of two zones of heat transfer <10 ° to the furnace as a whole, gives distorted results in the analysis of this factor can be seen more clearly than with other factors.

Application to the analysis of mathematical models constructed on the basis of consistency of parametric analysis, as well as the adequacy of simultaneous reflection on the possibilities of all the processes and indicators on all parameters, not only made it possible quantitatively to assess the impact of initial parameters on the final results (coke consumption, productivity), as well as reveal the internal communication processes in the volume of the furnace (including some new) that affect the nature of the modes and results of melting, and quantitative influence on the coke consumption of the nature of heat and mass transfer, phase transformations, gas-dynamic and distribution of materials and gases in a furnace, connected direct and feedback with the coke consumption.

At the same time identified and clarified some regularities of the course of the process, some of which qualitatively confirmed the previous experimental studies. The regularities of transformation of temperature - concentration phase and gas-dynamic fields in the BF volume and cross flows of gas at high column of the charge help to explain a number of complex phenomena and can be considered as tools of self-regulation in a large system "Blast smelting", and established a complex system of forward and backward linkages of the parameters of the zone of softening and melting, and heat loss through walls with a set of input, intermediate and output parameters of the blast furnace is an important component of the system analysis of smelting.

Further study of this system is considered the method with the addition of new experimental studies will reveal new regularities of the development processes and additional system properties that can be used to improve technology. It is primarily the achievement of the lowest possible level of coke consumption, which we estimate at 180-200 kg/t of cast iron. Decrease of coke consumption up to this level cannot be achieved only by traditional methods. One of radical ways of solution of this problem is the injection of coal gasification products developed by us based on the foundations of the technology and preforming gasifiers. Further evolution will follow the path of non-coke smelting in shaft-hearth unit on the basis of the blast furnace. In parallel to the development of the energy, sanitation and ecological functions of blast furnaces by rebuilding decommissioned by the balance of the metal aggregates in the mode of gasification of coal and disposal of waste as well as smelting of ferro-alloys. This concept of the development of metallurgy meets the evolutionary nature of progress in this industry, spanning the deep socio-economic strata of the social organism. In the final stage of this evolution creates non-coke technology of obtaining of metals in mine-hornbeam unit on the basis of the blast furnace [1]. This technology has been successfully opposed in the competition of alternative (liquid-phase reduction-LPR, COREX, ...etc.) and remains a priority for a long period, leaving place to others under certain conditions: for example, the construction of the facility LPR in the blast furnace plant in the event of an increase in the number of recyclables.

In the period 1967 - 2017 Iron and Steel Institute NAS of Ukraine studies of the system analysis of blast furnace smelting in the framework of the annual research work "Analysis of the operation of blast furnaces" commissioned by the Ministry of Metallurgy. The results of the work contain generalizing characteristics of processes and the principles of the functioning of systems used in the analysis of existing technologies and the development of new ones. The indicated time-indicators and characteristics are available to all Russian-speaking consumers thanks to a large number of publications in Russian. Publication of this generalizing monograph in English will fill the deficiencies of information in this field and increase the possibilities of system analysis of blast furnace smelting.

2. MINIMIZATION OF COKE CONSUMPTION AND PROBLEMS OF LOW-COKE TECHNOLOGY

2.1. System analysis of the processes under influence of the complex of parameters

Consideration of the blast smelting 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 and mass transfer. Another essential requirement of the system analysis is the interrelatedness of parameters, which is implemented through the adequacy of the models of processes.

Influence on the 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 intersecting 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) [5, 6, 21].

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.

2. 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.

3. With an increase in blast temperature T_b in the case of EDB in the high-temperature zones (900°C - t_{ml}), 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°).

4. 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 T_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: 5000-m^3 BF-9 at ArselorMittal 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 [26, 27]. 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 physic-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 in. 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 [15, 16, 25].

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 [15, pp.363-373]. It was shown that:

1) 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 physic-mechanical characteristics and it is possible to form axial and peripheral vents whose parameters can be continuously controlled;

2) 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;

3) 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 permeability’s 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 2.1 shows graphs of the OB distribution with the EBD and a UBD.

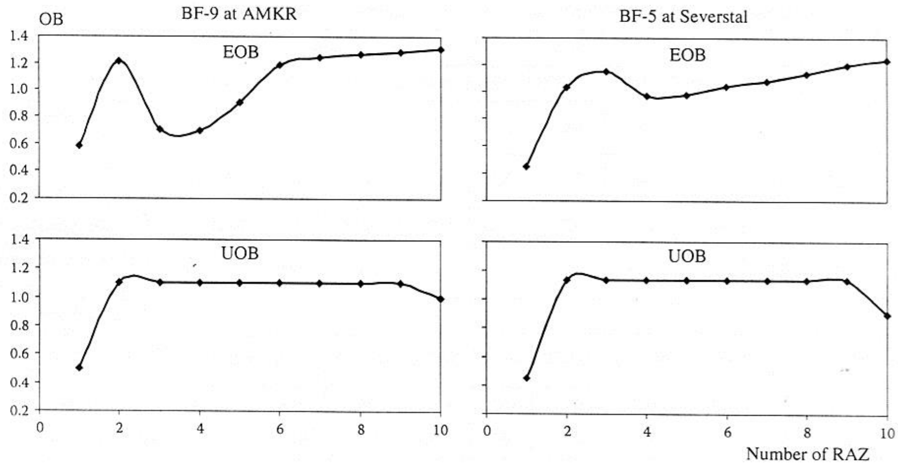

Fig.2.1. Relative ore burdens (OBs) in radial annular sections (RAZs) – existing ore burdens (EOBs) and uniform ore burdens (UOBs)

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 2.1 shows the results obtained from the calculation of several variants in which as much coke as possible was replaced. Figure 2.2 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).

Table 2.1. Main theoretical performance indices of BF operated with replacement of 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 lump fuel, kg/ton	505	304	250	215	286	214	200	421	276	222	257	179
Blast temperature, °C	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 temperature, °C	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, °C	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 Fe, %	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

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 a PCF consumption in the range 219-260kg/iron [26, 27].

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. 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 [15, pp.600-603].

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 Fig. 2.2). 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 [24, 28]. 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.).

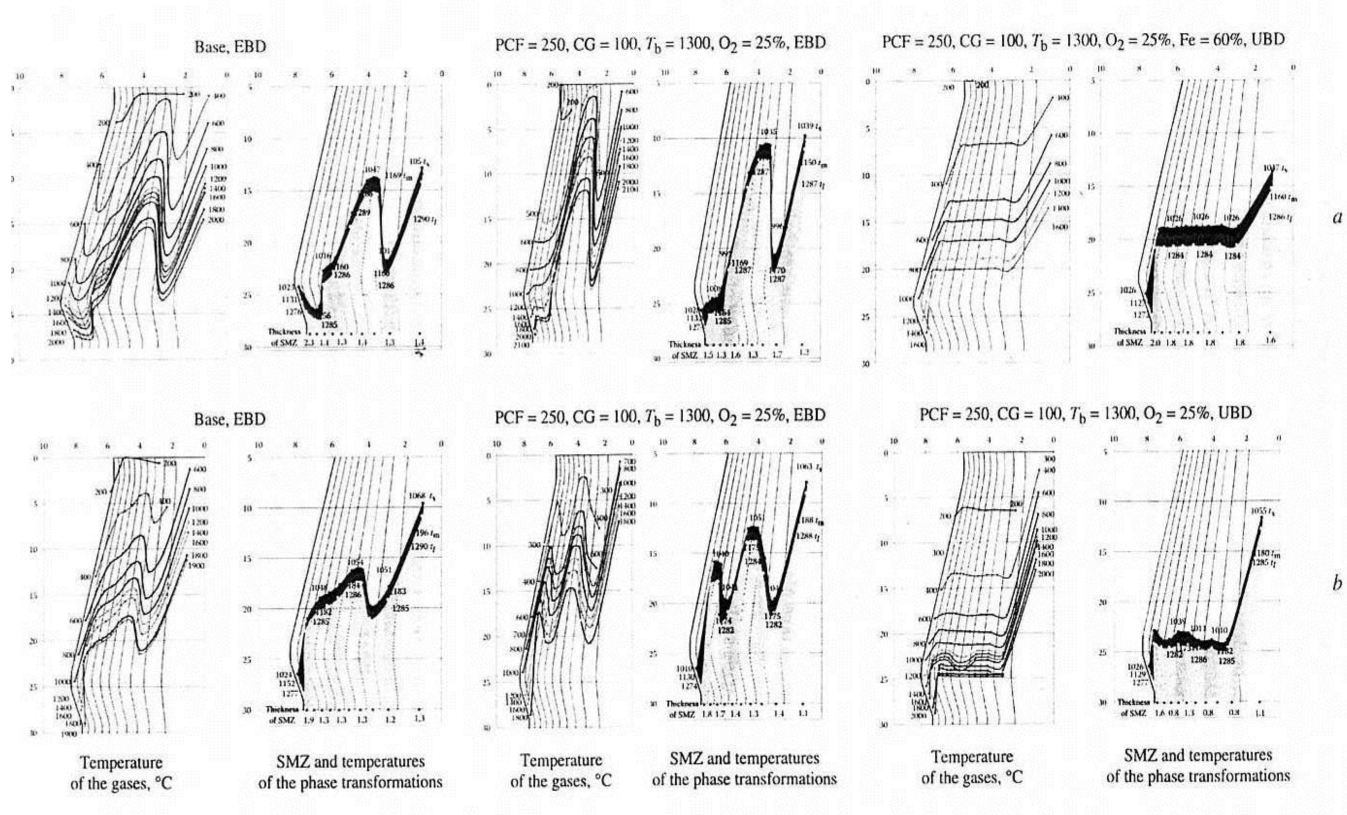

Figure 2.2. Distribution of gas temperature T and position of the softening and melting zone (SMZ) in BF-9 AMKR (a) and BF-5 Severstal (b) with different parameters. Along the horizontal – distance from the furnace axis; along the vertical – distance from the top (technological datum level), m

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 [23-25, 28] and although the attendant difficulties can be overcome 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 [24, 28]. 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 [23], 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 [23] 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. As regards the injection of hot reducing gases - coal-gasification products (HRG-CGP), the authors of [23] 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 [25].

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 [15, 16]) 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 [22]. 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.

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) [15, 16]. Although theoretical interest in solving the above problem has not waned since work on such a technology began during the period 1980-1982 [29], 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 [88] 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 [15, 16].

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 to cut expenses coke 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.

Table. 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 lump fuel, kg/ton	505	304	250	215	286	214	200	421	276	222	257	179
Blast temperature, °C	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 temperature, °C	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, °C	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 Fe, %	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

2.2. New blast smelting technology by injecting coal gasification products

Two most promising known non-traditional blast furnace technologies can be used to minimize the coke rate:

- the tuyere injection of the hot reducing gases with removal of CO_2 from the top gas and 100% oxygen blast developed by Tulachermet [30];
- injection of 300-400 kg pulverized coal/thm (PCI-technology).

The injection of hot reducing gases (HRG) is limited by the heat balance of the entire Iron & Steel Works since the blast furnace gas will not be supplied to other works in sufficient quantity. The combustion and gasification of significant amount of coal and liquation of coal ash in the tuyere's raceway are the limitations for the PCI-technology. Lack of resources, low-ash coal for pulverized coal injection (PCI) requires solutions to technical problems of the use of high-ash coals, in particular, partial and full gasification of fuel before entering the tuyere area of BF.

These problems can be resolved by the installation of the coal reactor-gasifiers for individual tuyere or for the whole furnace. This new technology of coal injection allows replacing of about 50-70 % of coke with low-grade coals with simultaneous increase in the furnace productivity. At the Institute of ferrous metallurgy of the NAS of Ukraine this problem was realized in 80-ies of the last century and then proceded to development, the results of which are set out below.

Low-coke technology of blast-furnace smelting (LCT)

Regularities of coal gasification and HRG injection

To increase the PCI rate and to allow higher ash coals to be used in the blast furnace it is reasonable to remove the process of coal gasification from the blast furnace. In this case the gasification takes place in an external coal gasifier with following injection of the hot reducing gas (HRG) into the tuyere raceway. Because of organized process of gasification and the possibility to remove the liquefied ash from the reactor-gasifier the volume of HRG injected into the furnace can be significantly increased. The additional amount of heat transferred to the furnace with HRG and the decrease in the direct reduction stipulates the decrease in the coke consumption.

Two types of reactor gasifiers can be used for production of HRG and their injection into the blast furnace: individual reactor-gasifier for each tuyere (TRG), and reactor-gasifier for the whole furnace (FRG). One of the blast furnaces or one stove can be used as the reactor-gasifier, if there is excessive blast or hot metal production capacity at the Iron & Steel Works.

Vortex type TRG for PCI was developed and tested by the Institute of High Temperatures of Russian Academy of Sciences. The principal schematics of such reactor – prototype for the industrial installation, is presented in Figure 2.3. The main element of this reactor is two-stage vertical chamber. The temperature of HRG produced is about 1,700-2,500 °C and the productivity is about 3-5 t of PCI/h, which is sufficient for 1 or even 2 tuyeres operation.

The ignition of PCI and its gasification in vortex flow with coefficient of air expenditure α = 0.4-0.5 occur in the first flashbox stage (1). The gasification is completed in the second stage (5). The whole reactor-gasifier is water-cooled. The melted slag particles are discarded to the reactor walls forming the liquid film of accretion, which flows down through the taphole (2) to the slag pot (3). The diaphragm (4) controls the gas and slag separation. The hot blast and the PCI enter the reactor-gasifier through the socket (6) and the HRG enters the tuyere through the socket (7).

The combination of the high volume of HRG and hot blast (HB) in the same tuyere is one of the major problems of a new technology. Simulations showed that increase in a volume, temperature and reduction potential of HRG reduces the required volume of HB and affect of HB preheating temperature on the blast furnace heat balance. Because of this, it is possible to replace the HB with the cold oxygen. The volume of cold oxygen is ten times lower the volume of HRG and it can be injected similar to natural gas injection.

The injection of the oxygen into the core of the HRG (not to the coke packing) is the main principle for oxygen injection. It could be achieved by the inclination of the injecting socket towards the HRG stream or by injection of the oxygen in a blanket of natural gas or cold reducing gas (CRG). The tuyere arrangement for this case is presented in Figure 2.4.

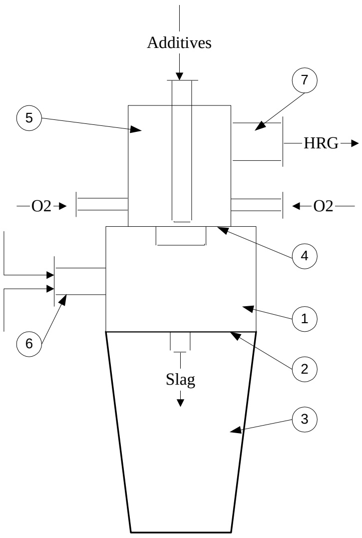

Figure 2.3. Schematics of reactor-gasifier

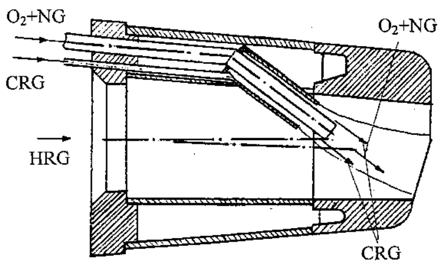

Figure 2.4. Arrangement of tuyere for HRG and oxygen injection

The other design of the “Tulachermet” tuyere with the oxygen injection into the stream of HRG near the tuyere tip is presented in Figure 2.5. This tuyere design was also successfully tested during the trials of reactor-gasificator.

The injection of the HRG into the tuyere raceway leads to the change in their operation. Because of absence of oxidizers in the HRG coke is not consumed and there is no gradient of coke velocity in the coke packing. As a consequence of this the porosity of the coke packing decreases reducing the drainage capability of material column.

The HRG injection with the HB or cold oxygen shifts the raceway operation towards the classical case. However, the required oxygen volume is determined by blast furnace's heat balance and the required raceway adiabatic flame temperature (RAFT) and because of this, is not necessarily in correspondence with requirements for coke packing mobility, which determines the counter-current flow in the bottom segment of blast furnace.

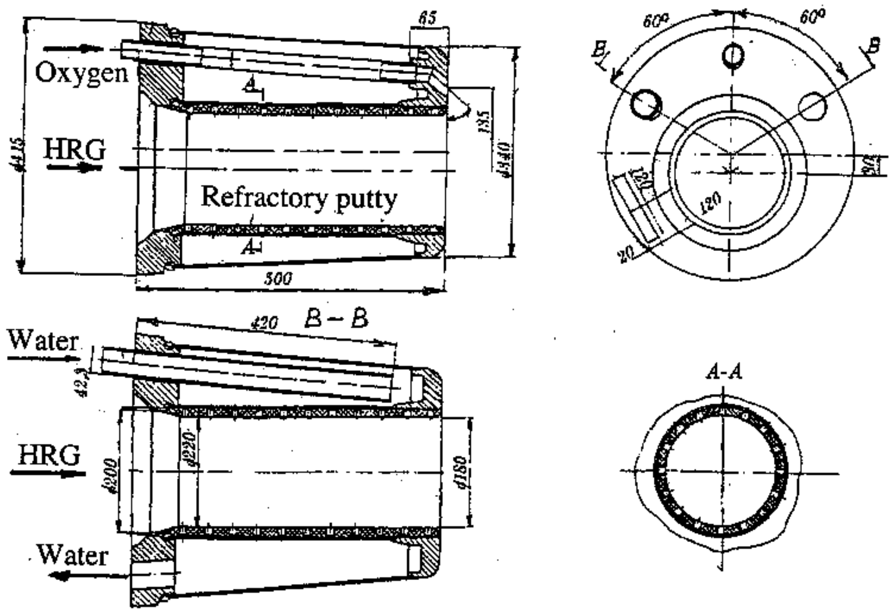

Figure 2.6. "Tulachermet" tuyere arrangement for HRG and oxygen injection

Decrease in the coke rate to 250-300 kg/thm with the same volume of liquid products of melting process leads to doubling of the liquids load on the coke packing. The fraction of direct reduction in this case is minimal and the content of wustite in the primary slag is minimal as well. This leads to retarding of the carbon dissolution in the slag, which also negatively affects the coke packing mobility.

This contradiction can be resolved by combined consideration of the all conditions of blast furnace operation. Increase in the coke packing mobility and porosity could be achieved by optimization of hot metal and slag tapping. The optimization of the burden would improve the slag properties. The decrease in a slag's wustite content could be overcome by the increase in HRG temperature without increase in reduction potential. For this purpose the coal gasification should be done by hot atmospheric or slightly enriched by oxygen blast without employment of pure oxygen.

The maximum efficiency of HRG injection into the blast furnace can be achieved in the case of production of high temperature HRG with low oxygen potential. The raceway conditions are more forgivable to the decreased RAFT (1800-1900 ^{0}C) in the case of HRG injection in comparison with classical PCI, oil or natural gas injection. This allows the injection of increased amount of HRG.

Reactor-gasifiers design

Various TRG designs were developed and tested by Institute of High Temperature of Russian Academy of Science and Institute of Ferrous Metallurgy of Ukrainian National Academy of Science. The design of TRG presented in Figure 2.7 was tested at the blast furnace at Tulachermet. Figure 2.8 illustrates the installation of the reactor at blast furnace tuyere.

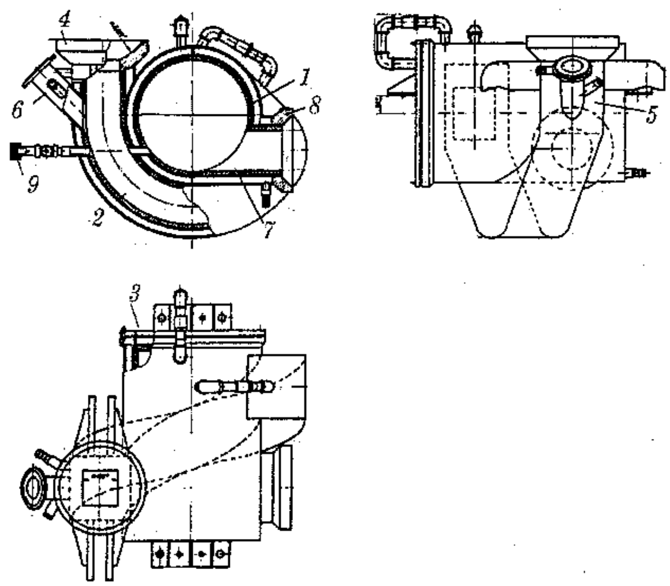

Figure 2.7. The tuyere reactor-gasifier tested at blast furnace

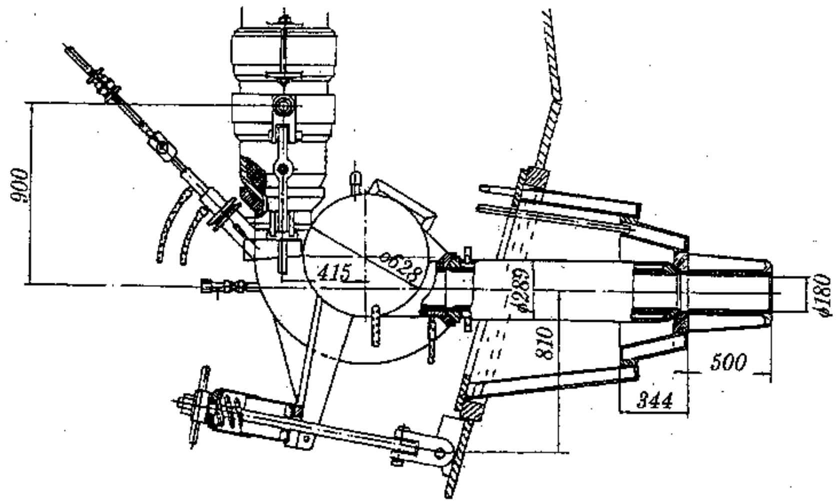

Figure 2.8. Installation of reactor-gasifier at blast furnace tuyere

The TRG (Figure 2.7) consists of water-cooled jacket (1) and screw trough (2). The removable lead (3) is installed at one of the sidewalls of reactor's chamber. The internal chamber diameter is 500 mm and the chamber width is 1,500 mm. The sockets (4) and (7) are connected to the bustle main downcomer leg and to the tuyere by spherical heads (5) and (8), respectively. The socket (9) is designed for visual control and for injection of compressed air if required.

The hot blast enriched by oxygen enters the TRG through the socket (4). The pulverized coal is injected into the TRG through the tuyere installed at the case of screw trough (2). The flow of HRG swirled in the cylindrical chamber enters the blast furnace tuyere through the socket (7).

The TRG is designed to be installed instead of the tuyere elbow and does not require any additional modifications (Figure 2.8).

The principle of central reactor-gasifier (FRG) installation for the whole blast furnace is shown in Figure 2.9.

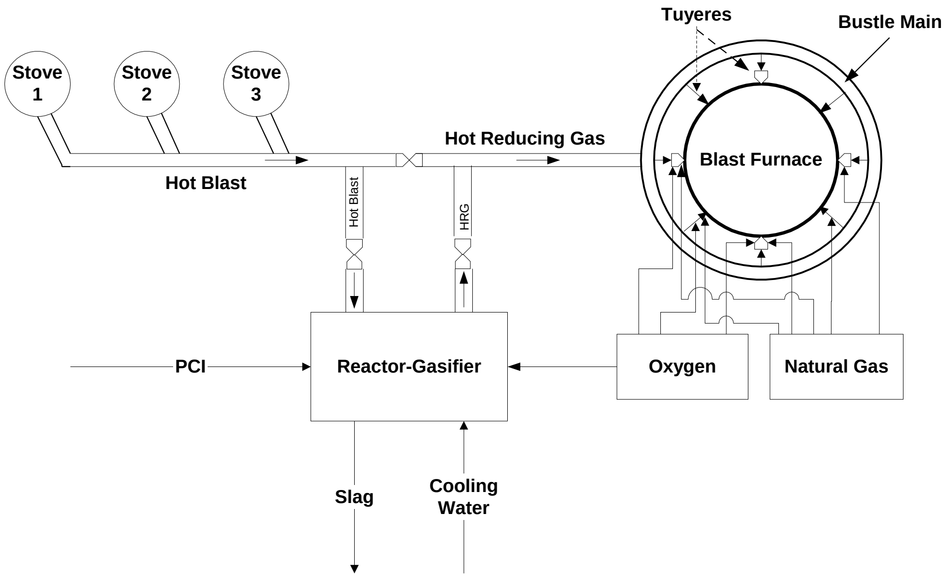

Figure 2.9. Principle schematics of blast furnace reactor-gasifier

Both TRG and FRG technologies have the positive and negative features. The possibility to inject into blast furnace the HRG with very high (up to 1700-1800°C) temperature is a benefit of the TRG arrangement. However, some liquid ash amount can be elutriated into the furnace raceway. FRG arrangement allows completely eliminate elutriation of liquid ash, however, the temperature of the HRG is limited by the refractory lining resistance of the bustle main and other hot temperature ducts.

Estimated results and analysis

The estimated results of Zaporogzstal's Blast furnace № 2 operation with FRG are presented in Table 2.2.

Table 2.2. Estimated results of Blast furnace № 2 operation with injection of HRG and oxygen

Parameter	Base case	Trial period
Specific productivity, thm/m^3 day	1.87	1.954
Dry coke rate, kg/thm	471	372
RAFT,' ^{0}C	2039	1900
Blast parameters:		
Blast rate, Nm^3/thm	1271	
Temperature, ^{0}C	1200	
Oxygen content, %	27	95
Oxygen consumption, Nm^3/thm	106	235
Natural gas rate, Nm^3/thm	152	
Fraction of natural gas in blast, %	12	
HRG consumption, Nm^3/thm	-	1481
HRG temperature, ^{0}C	-	1200
HRG composition, %;		
CO		32
H_2		20
CO_2		0
H_2O		0
N_2		48
Coke carbon burned at tuyeres, kg/thm	290	242
Raceway gas volume, Nm^3/thm	1953	1947
Top gas volume (wet), Nm^3/thm	2109	2034
Top gas temperature, ^{0}C	321	340
Top gas composition, %		
CO_2	16.89	22.06
CO	22.74	27.32
H_2	9,65	8.94
H_2O	7.17	7.17
N_2	43.54	34.51
Indirect reduction, %	70	87.9
Blast furnace gas utilization, %	42.62	44.68

Table 2.2 results allow to conclude that injection of HRG with temperature of 1200 ^{0}C without oxidizing components, natural gas and with hot blast replacement by cold oxygen saves 99 kg of coke per tone of hot metal. To produce 1481 Nm^3/thm of HRG it is necessary to consume 375 kg of coal/thm and 890 Nm^3/thm of blast. Additional 70 kg/thm of limestone are required for adjustment of slag composition (with respect to the decrease in coke consumption).

The potential benefits of the new technology with TRG were estimated with respect to the Zaporozgstal's blast furnace № 5 operation. The operation of the blast furnace in 1993 was chosen as the base case. The consumption of reference fuel (RF) with LHV=29,309 kJ/kg was used as a parameter for estimation of the total energy required to produce one ton of hot metal. The LHV of coke and coal's carbon and natural gas were assumed as 33915 kJ/kg and 34490 kJ/Nm^3, respectively. The consumption of reference fuel for other variable consumables were assumed as follows: coke production – 0.14 kg RF/kg of coke; blast compression – 0.03 kg RF/Nm^3 of blast; oxygen production – 0.25 kg RF/Nm^3 of oxygen; blast preheating – according to the blast enthalpy with heating efficiency of 0.75. The results of calculations are presented in Table 2.3.

Table 2.3. Benefits of blast furnace operation with replacement of natural gas with HRG

Parameter	Base case	HRG with T_{blast}=1000^{0}C	HRG with T_{blast}=1200^{0}C
Specific productivity, t/m^3 day	1.32	2.03	2.06
Coke rate, kg/thm	565	334	305
Natural gas rate, Nm^3/thm	71	-	-
Coal consumption, kg/thm	-	290	300
Oxygen consumption, Nm^3/thm	38	180	150
Blast rate, Nm^3/thm	1630	675	700
Blast temperature, ^{0}C	1011	1000	1200
RAFT, ^{0}C	2025	2030	2020
HRG volume, Nm^3/thm	-	990	1020
HRG composition, %			
CO	-	32.5	32.5
CO_2	-	0.5	0.5
H_2	-	12.4	12.4
H_20	-	0.5	0.5
N_2	-	54.1	54.1
C_{solid}, g/Nm^3	-	19.7	19.7
HRG temperature, ^{0}C	-	1540	1650
Direct reduction, %	38	30	32
Total RF consumption, kg RF/ ton hot metal	895.8	798.4	780.4
Top gas calorific value, kg RF/ ton hot metal	275.1	242.5	229.9
Top gas to external customers, kg RF/ ton hot metal	165.2	197.5	173.9
Net RF rate for the process, kg RF/ton hot metal	730.6	600.9	606.5

Results of this table lead to the following conclusions on the influence of HRG injection on blast furnace performance:

The coke consumption decreases by 41-46 %

Productivity increases by 1.53-1.56 times

Total reference fuel consumption decreases by 97.3 and 115.4 kg RF/thm, respectively

The net reference fuel rate for the process also decreases by 129.7 and 124.1 kg RF/thm while the amount of the top gas sold to external customers increases by 32.3 and 8.7 kg RF/thm, respectively.

The capital expenditure for the equipment of the blast furnace with TRG is estimated by Ukrainian Gipromez in the range of 11-12.2 mill. Euros depending on the type of the coal supplied to reactor-gasifiers (coarse or PCI). This is almost half as much in comparison with traditional PCI technology. The payback period is estimated in the range of 0.7-1 year depending on the type of coal for gasification.

Analytical study of blast-smelting technologies with injection of coal-gasification products

Given the acute shortage of the necessary grades of coal, it might be possible to reduce coke consumption to 200 kg/ton iron by using low-grade coals as a substitute for coke. This approach might prove workable if it is pursued based on the development of a new blast-furnace smelting technology that involves the injection of hot reducing gases (HRGs) -coal-gasification products (CGPs) obtained in special gasifiers. The latter can be either furnace-side units (for certain furnaces) or tuyere-mounted gasifiers (TMGs).

The essence of the technology involving CGP injection with the use of TMGs is as follows. The knee-nozzle section of each blast-furnace tuyere is equipped with a TMG - a device to gasify PCF. Hot blast is fed from the overlying bustle pipe through an opening in the TMG and is injected with PCF the HRGs-CGPs generated in the device are directed out of the TMG and into the tuyere hearth. The TMG developed by specialists at the Institute of Ferrous Metallurgy and the Institute of High Temperatures (IVTAN) is based on design elements incorporated into a vortex reactor-gasifier invented earlier by IVTAN. The part of the oxidizing blast that enters directly into the blast furnace for coke combustion is delivered via a separate channel. This channel can be made in one of two variants:

1) it is possible to install an independent hot-blast pipe that branches off the bustle pipe and feeds directly into the tuyere for introduction of the blast into the furnace;

2) part of the hot blast can be replaced by an equivalent amount of unheated oxygen delivered to the tuyere hearth by a pipe that (as in the injection of natural gas) extends through the tuyere (in this variant, the CGPs travel along the tuyere's main channel).

The high degree of completeness of PCF gasification in a TMG and the fact that the ash part is fully fluidized and carried into the blast furnace ensures efficient combustion of coke in the tuyere hearth. In contrast to the standard method of PCF injection, the TMG makes it possible to use a wide range of high-ash coals for blast-furnace injection.

An analytical study was performed to establish the principles behind this technology and evaluate the expediency of its further development and practical introduction.

Method of Investigation and data source.

To systematically evaluate the effect of the main parameters of the technology on blast furnace smelting indices, we used a mathematical model developed at the Institute of Ferrous Metallurgy [15, 16, 21]. To analyze the new smelting technology with HRG-CGP injection in special gasifiers, the mathematical model of the smelting operation was supplemented by a model constructed to design a

TMG for coal. The quantity, composition, and temperature of the agent being gasified and the oxidant are entered into the TMG model and the theoretical parameters of the PCF (number, temperature, and composition) are obtained at its output. These parameters are then entered into the smelting model.

As the basis for our calculations, we chose the operating conditions of 5500 m^3 blast furnace № 5 at the Severstal and the 5000 m^3 blast furnace № 9 at the ArselorMittal Krivoy Rog (henceforth referred to as AMKR). These furnaces were operated in their base regimes with the following distributions of the relative ore burden (OB) in the rotary distributor (RDR) at the top of the furnace:

No of RDR	1	2	3	4	5	6	7	8	9	10
OB of BF-5	0,45	1,03	1,15	0,97	0,98	1,04	1,08	1,14	1,20	1,24
OB of BF-9	0,49	0,98	1,08	1,08	1,08	1,03	1,08	1,09	1,09	1,23

The compositions of the coals chosen for the calculations are shown in Table 2.4.

Table 2.4. Compositions of coals used to calculate blast-furnace Indices and parameters with the Injection of PCF and CGPs

Coals for Injection	Ash, %	Volatile matter, %	S, %	H, kg/kg	N, kg/kg	O, kg/kg	H_2O, kg/kg	$C_{vol,}$ kg/kg	C_{Σ}, kg/kg	C_{nonvol} kg/kg
PCF_{HG} (AMKR)	10	13	1.2	0.04	0.015	0.025	0.01	0.05	0.798	0.748
CGP_{LG} (AMKR)	25	25	1.2	0.05	0.025	0.075	0.01	0.10	0.578	0.478
PCF_{HG} (Severst.)	10	13	0.5	0.04	0.015	0.025	0.01	0.05	0.805	0.755
CGP_{LG} (Severst.)	25	25	0.5	0.05	0.025	0.075	0.01	0.10	0.585	0.485

Table 2.5. Projected Blast-Furnace Smelting Indices on BF-5 at Severstal *(V =* 5500 m^3) with the Injection of PCF, PGUs, and Oxygen (O)

Indices	Base	PCF_{HG} 250	PCF_{LG} 400	CGP_{LG} 400	CGP_{LG} 400O	CGP_{LG} 450	CGP_{LG} 450O
Unit productivity,	1.736	1.739	1.533	1.441	1.523	1.373	1.403
Coke rate, kg/ton iron	427	239	240	267	279	249	289
Blast: wind rate, nr/min	7853	6892	6710	2177	879	1719	715
temperature, °C	1184	1184	1184	1184	20	1184	20
oxygen content, %	24.3	24.3	24.3	24.3	90	24.3	90
Natural-gas consumption	106	0	0	0	0	0	0
Consumption of injected	0	250	400	400	400	450	450
Top gas:							
temperature, °C	263	205	248	239	298	239	250
content, %: CO	21.7	21.2	22.9	22.5	22.5	23.1	25.3
CO_2	19.1	22.8	19.6	18.1	21.8	17.1	17.8
H_2	7.5	4.3	7.8	7.3	7.1	8.0	8.2
Limestone/converter slag,	3/5	8/5	78/5	81/5	82/5	92/5	93/5
Sinter + pellets + ore,	1585	1581	1565	1566	1565	1 563	1563
Iron in the charge, %	59.7	59.6	58.1	58.1	58.0	57.8	57.8
Ore burden, tons/ton	3.73	6.66	6.86	6.18	5.93	6.65	5.74
Total dust generation,	24	21	21	22	22	22	21
In the slag,*%:							
Silica	36.61	34.66	35.37	35.52	35.64	35.61	35.61
Alumina	8.42	8.0	9.76	9.86	9.92	10.07	10.07
Lime	38.42	36.37	37.12	37.28	37.40	37.37	37.37
Magnesia	11.56	10.73	8.86	8.84	8.84	8.62	8.62
Amount of slag, kg/ton	270	293	391	393	394	410	410
Blast consumption,	1184	1038	1146	396	151	328	133
Volume of moist gas,	1857	1603	1883	2075	1965	2171	2176
Oxygen consumption	58	51	56	19	147	16	130
Theoretical combustion temperature, °C	2007	2 1 39	1942	1836	1876	1784	1804
Quantity of tuyere gas, m^3/ton	1713	1443	1735	1929	1875	2022	2039
Quantity of dry top gas, m^3 /ton	1737	1527	1763	1958	1836	2048	2056
Direct reduction of oxides of Fe, *%*	26.2	33.0	23.7	22.4	7.2	22.4	18.8
Use of CO + H_2, %	46.8	51.9	46.0	44.5	49.1	42.3	41.1
Lump carbon, kg/ton: total/in the tuyere region	367/257	206/82	207/97	230/122	240/163	215/106	249/148
Total heat input, kJ/kg	4524	4483	4804	4971	4845	5093	5098
including: coke combustion	2522	800	947	1197	1597	1041	1449

Indices	Base	PCF_{HG} 250	PCF_{LG} 400	CGP_{L} G400	CGP_{LG} 400O	CGP_{LG} 450	CGP_{LG} 450O
heat of blast and additions	1944	3629	3801	3717	3190	3994	3592
Heat requirements, kJ/kg	3178	3422	3524	3342	2963	3383	3286
Enthalpy of top gas, kJ/kg	788	512	729	1039	1334	1101	1213
Heat losses, kJ/kg	558	549	552	591	547	608	599
Percentage of useful heat, %	70.2	76.3	73.4	67.2	61.2	66.4	64.5
Ratio of water equivalents	0.776	0.845	0.745	0.750	0.771	0.712	0.749
Calorific value of top gas, kJ/m^3	3551	3147	3740	3628	3611	3795	4092
Rate of:							
gas use, $m^3/(m^3 \cdot min)$	2.238	1.935	2.004	2.076	2.078	2.069	2.120
coke use/lBC, kg/(m^3 ·day)	726/ 2730	408/ 2728	361/ 2380	377/ 2239	416/ 2366	335/ 2129	397/ 2176
CGP**:							
quantity, m /ton iron	-	-	-	1389	1546	1563	1739
temperature, °C	-	-	-	1707.9	1635.4	1708	1635
content of CO+H_2, %	-	-	-	29.1 + 16.2	26.1 + 14.6	29.1 + 16.2	26.1 + 14.6
CG blast* (1184°C), m^3/ton iron	-	-	-	943.1	1098.1	1061.0	1235.4
O_2 content of CG blast, %	-	-	-	24.3	20.8	24.3	20.8
Coke replacement equival-t kg/kg	-	1.108	0.693	0.625	0.595	0593	0507
* With iron containing the following in all variants, %: Si 0.65; Mn 0.4; S 0.016. Slag basicity 1.05.** With a prescribed O/C ratio = 0.6 mole/mole							

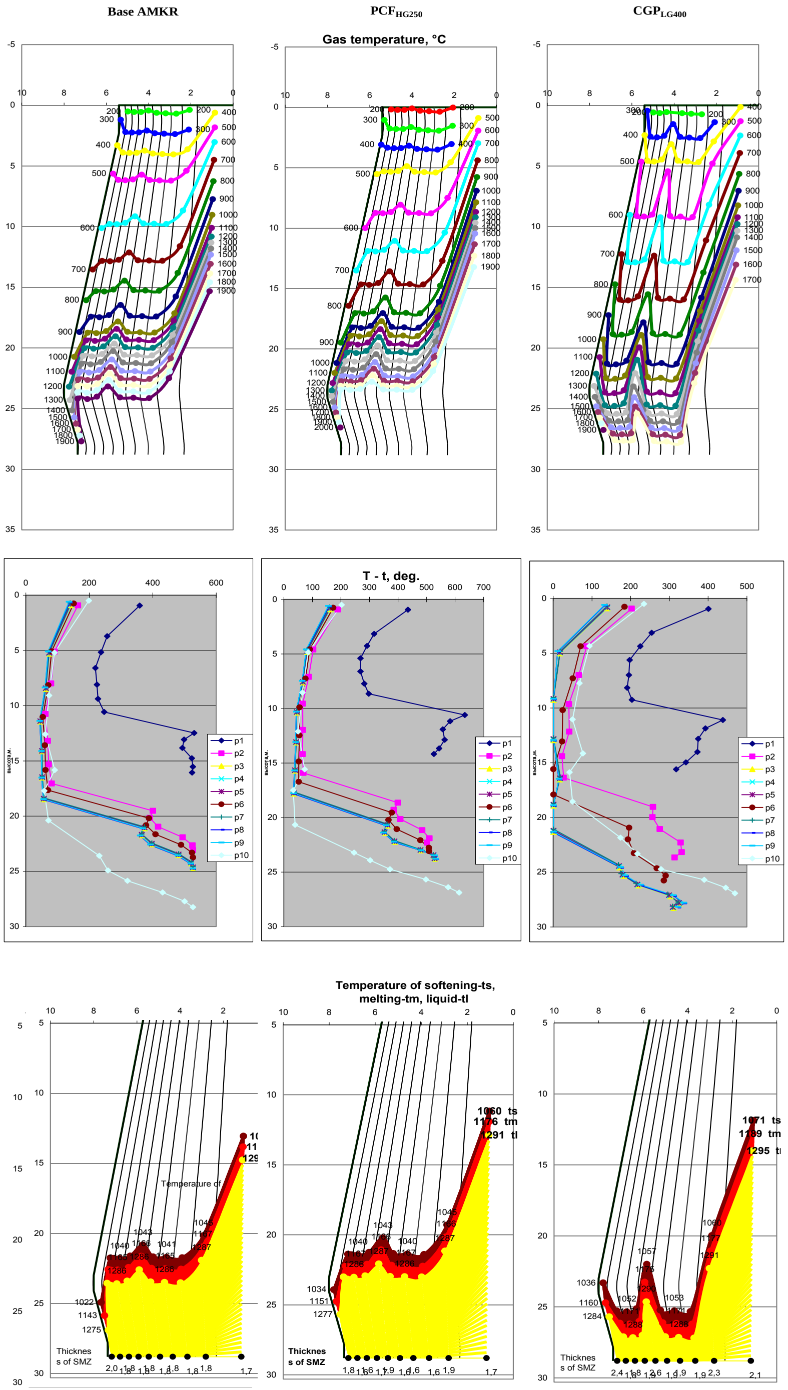

Figure 2.10. The temperature field of the gas, difference between the gas and charge temperatures (T - t) in the furnace and the location of the softening-melting zone (SMZ). The vertical distance - from the top, horizontally - from the furnace axis, m

Analysis of the research results

Tables 2.5 and 2.6 show the main theoretical indices and parameters of the processes for BF-5 at Severstal and BF-9 at AMKR, respectively. Figure 2.10 show the corresponding results in graphical form.

The design variants of the technology were as follows (with natural gas (NG) excluded):

1 - injection of PCF prepared from high-grade coals (PCF_{HG}) and injected at a rate of 250 kg/ton iron (PCF_{HG250});

2 - injection of PCF prepared from low-grade coals (PCF_{LG}) and injected at a rate of 400 kg/ton iron (this variant was not actually used and was included in the calculations only for analytical purposes - PCF_{LG400});

3 - injection of CGP prepared from low-grade coals (CGP_{LG}) and delivered to the coal TMG at rates of 400 and 450 kg/ton iron along with part (a corresponding amount) of the hot blast, which is injected through the tuyeres (CGP_{LG400}; CGP_{LG450});

4 - same as in (3) above except that cold oxygen is injected through the tuyeres instead of hot blast ($CGP_{LG400}O$; $CGP_{LG450}.O$)

The calculations for variants 3 and 4, involving the injection of CGPs, were performed with the assumption that \\Q^c/c of the heat in the CGPs is lost in the injection process.

Table 2.6. Projected Indices of Blast-Furnace Smelting on BF-9 (V = 5000 m^3) at AMKR with the Injection of PCF, CGPs. and Oxygen (O)

Indices	Base	PCF_{HG250}	PCF_{LG400}	CGP_{LG400}	$CGP_{LG400}O$	CGP_{LG450}
Unit productivity, tons/m^3 day	1.35	1.36	1.24	1.15	1.17	1.11
Consumption of lump fuel, kg/ton	494	302	297	332	419	308
including coke/anthracite	469/25	287/15	282/15	315/16	398/21	293/15
Blast:						
wind rate, m /min	5644	5281	5114	2196	987	1879
temperature, °C	1100	1100	1101	1100	20	1100
oxygen, %	27	27	27	27	90	27
Consumption of natural gas, m/ton	95	0	0	0	0	0
Consumption of injected coal, kg/ton	0	250	400	400	400	450
Top gas:						
temperature, °C	240	271	241	265	265	273
content, %: CO	26.2	25.8	26.5	25.8	31.8	25.8
CO_2	17.7	20.5	18.5	17.3	17.7	16.8
H_2	7.6	4.8	8.2	7.6	8.3	8.3
Charge: sinter + pellets + ore, kg/ton	1630	1631	1612	1611	1611	1608

Indices	Base	PCF_{HG250}	PCF_{LG400}	CGP_{LG400}	$CGP_{LG400}O$	CGP_{LG450}
Enriched converter slag/Limestone	119/21	119/29	118/111	118/116	118/116	117/129
Iron in the charge, %	54.6	54.4	53.1	53.0	53.0	52.8
Ore burden, tons/ton	3.6	5.9	6.2	5.6	4.4	6.0
In the slag.* %:						
silica	38.3	37.0	36.7	36.9	36.9	36.7
alumina	6.5	6.2	7.6	7.8	7.8	7.9
lime	46.7	45.1	44.7	45.0	45.0	44.8
magnesia	4.9	4.7	4.2	4.2	4.2	4.1
Amount of slag, kg/ton	438	464	567	569	569	586
Blast consumption, m^3/ton	1196	1110	1183	546	241	484
Volume of moist gas, m^3/ton	1917	1737	1976	2185	2187	2264
Oxygen consumption (calc), m^3/ton	106	99	105	49	240	43
Theoretical combustion temperature, °C	2122	2227	2023	1930	2020	1877
Quantity of tuyere gas, m^3/ton	1734	1562	1810	2025	2022	2111
Quantity of dry top gas, m^3/ton	1806	1662	1861	2069	2081	2141
Direct reduction of oxides of Fe, %	30.2	33.2	23.6	20.2	20.2	18.0
Use of CO + H_2, %	40.3	44.2	41.0	40.0	35.6	39.2
Consumption of lump carbon, kg/ton	412	252	248	276	350	257
including from coke at the tuyeres	300	134	142	178	251	162
Total heat input, kJ/kg	4877	5020	5205	5464	5569	5564
including: coke combustion	2943	1314	1398	1743	2460	1585
heat of blast and additions	1815	3595	3692	3604	2991	3862
Heat requirements, kJ/kg	3751	3904	4073	3795	3801	3789
Enthalpy of top gas. kJ/kg	746	743	748	1182	1272	1279
Heat losses, kJ/kg	380	374	384	488	496	497
Percentage of useful heat, %	76.9	77.8	78.3	69.5	68.3	68.1
Ratio of water equivalents	0.802	0.832	0.757	0.807	0.854	0.772

Indices	Base	PCF_{HG250}	PCF_{LG400}	CGP_{LG400}	$CGP_{LG400}O$	CGP_{LG450}
Calorific value of top gas, kJ/m^3	4140	3783	4238	4091	4913	4162
Rate of:						
gas use, $m^3/(m^3 \cdot min)$	1.797	1.641	1.697	1.745	1.776	1.745
coke use, kg/(m^3·day)	653	403	359	373	480	335
ore use, kg/(m^3 ·day)	2314	2334	2096	1947	1980	1876
CGP*: amount, m^3/ton iron	-	-	-	1282	1282	1443
temperature, °C	-	-	-	1706	1568	1706
content, %: CO	-	-	-	31.2	31.2	31.2
H_2	-	-	-	17.4	17.6	17.4
Gasification blast:						
amount, m^3/(ton·h)	-	-	-	839	1073	944
temperature, °C	-	-	-	1100	1100	1100
O_2 content, %	-	-	-	27	21	27
O_2, consumption, m^3/ton iron	-	-	-	75	3	85
Coke replacement equivalent, kg/kg	-	1.09	0.69	0.61	0.39	0.59

* With iron containing the following in all variants, %: Si 0.81; Mn 0.48; S 0.022. Slag basicity 1.22.
** With a prescribed O/C ratio = 0.6 mole/mole

The size of the reduction in coke consumption (ΔC, kg/ton iron) that takes place when PCF and PGU are injected into the furnaces instead of NG was determined based not only on the carbon and ash contents of the coals (see Table 2.4) but also on the changes in the amount of slag in the furnace ΔS, kg/ton iron), the amount of raw limestone in the furnace (ΔL, kg/ton iron), top-gas temperature (Δt_t , deg), the degree of direct reduction (Δr, %), and the heat loss (Δq, rel.%). Table 2.7 shows the results of the calculations and the equivalent for the replacement of coke by coal (E_r ,kg/kg).

It follows from the data which are presented here that if high-grade PCF injected at the rate 250 kg/ton were to be replaced by low-grade PCF, the rate of injection of the latter would have to be increased to 400 kg/ton in order to save the same amount of coke. The second variant just alluded to is only hypothetical, since the injection of PCF prepared from high-ash grades of coal (especially in large quantities) would sharply reduce the completeness of combustion of the carbon in the coal and the degree of fluidization of the ash portion. That would in turn render the technology useless. The technology can be successfully implemented if the PCF undergoes preliminary gasification so that CGPs (see above) are instead delivered to the tuyere hearths. The amount of coke saved would decrease somewhat in this case due to the additional heat losses incurred as a result of cooling of the TMG (in the variant CGP_{LG400}). Even less coke would be save if hot blast were replaced by cold oxygen (the variant $CGP_{LG400}O$). It might be possible to recover a part of these losses by increasing the amount of CGPs that is injected (by using the variants CGP_{LG450} and $CGP_{LG450}O$).

Table 2.7. Results of Calculations Performed for Four Variants of PCF and CGP Injection on BF-5 at Severstal and BF-9 at AMKR

Indices	PCF_{HG250}	PCF_{LG400}	CGP_{LG400}	$CGP_{LG400}O$	CGP_{LG450}	$CGP_{LG450}O$
BF-5 Severstal						
CGP, m^3/ton	-	-	1389	1546	1563	1739
ΔC. kg/ton	-188	-187	-160	-148	-177	-138
ΔS. kg/ton	+23	+ 121	+ 124	+ 125	+ 140	+ 140
ΔL. kg/ton	+5	+75	+78	+79	+89	+90
Δt_t ,deg	-58	-15	-24	+35	-24	-13
Δr. %	+6.9	-2.5	-3.8	-19.0	-3.8	-7.4
$\Delta q_>$, %	-1.6	-1.1	+5.9	-2.0	+9.0	+7.3
E_r , kg/kg	1.108	0.693	0.625	0.595	0.593	0.507
BF-9 AMKR						
CGP, m^3/ton	-	-	1282	1282	1443	-
ΔC. kg/ton	-172	-177	-162	-74	-186	-
ΔS. kg/ton	+26	+ 119	+ 121	+ 121	+ 148	-
ΔL. kg/ton	+8	+90	+95	+95	+ 108	-
Δt_t, deg	+31	+ 1	+25	+25	+33	-
Δr, *%*	+2.9	-6.7	-10.1	-10.1	-12.3	-
$\Delta q_>$, *%*	-1.6	+ 1.0	+2.1	+30.5	+30.5	-
E_r kg/kg	1.09	0.69	0.61	0.39	0.59	-

The temperature field of the charge and the gas flow in the furnace and the location of the softening-melting zone (SMZ) change with an increase in the consumption of CGPs. These changes are analogous to the changes that take place with an increase in the consumption of PCF (see Fig.2.10), and the same tendencies are also seen with the injection of natural gas and coke-oven gas [15, 16, 21]. However, the changes are quantitatively smaller and are different for different charges and different charge distributions in the furnace.

When NG (95 and 101 m^3/ton) was replaced by CGPs (1282-1739 m^3/ton), the degree of direct reduction decreased on both furnaces. In the variants in which the latter dropped to below 20%, top-gas temperature tended to rise faster with an increase in CGP injection rate. This finding is consistent with the previously established rule stating that two-stage heat exchange in a blast furnace undergoes a transformation with a decrease in the quantity of endothermic material in the charge in the direct-reduction region and dissociation of the carbonates in the furnace [15, 16, 21].

The unit heat losses change as a result of a decrease in gas temperature in the lower part of the furnace, which is accompanied by a substantial decrease in its productivity. The ultimate outcome is an increase in heat loss in the main variants described above.

The results just reported were typical of both furnaces when the technology entailed diverting part of the hot blast from the bustle pipe to the TMGs for PCF gasification and directing the remaining blast into the tuyere hearths for coke combustion.

Somewhat different results were obtained when part of the hot blast was replaced by unheated oxygen. This variant was proposed with the objective of being able to use tuyeres with a more compact design. In this case, the need for blast oxygen to burn the carbon in the coke was low on BP-5 due to the low initial and projected consumptions of coke carbon in the tuyere region. Thus, replacement of part of the hot blast by cold oxygen was accompanied by a moderate increase in coke consumption. Such an increase might be acceptable if it in turn is accompanied by an increase in the productivity of the furnace. As for the operating conditions on BF-9 at AMKR, with a higher initial and projected consumption of coke carbon in the tuyere region, the need for blast oxygen to burn that carbon was relatively great. This situation led to an increase in coke rate as the supply of hot blast was curtailed. The increase in coke consumption was roughly the same as the amount of coke that was saved by CGP injection, and the operation of the furnace became less stable as well.

The equivalent for the replacement of coke by coal-gasification products (kg/kg) was found by correcting the coke savings realized in each variant based on the coke equivalent of the natural gas eliminated from the smelting operation and then dividing the corrected figure by the consumption of gasified coal. It follows from the results presented above that the values of E_r which correspond to the variants employed on the two blast furnaces are similar except for the variant in which hot blast was replaced by unheated oxygen. The results obtained in this case have already been discussed. The ratio of the equivalent for the replacement of coke by low-grade coal (in the form of CGPs) to the equivalent for the replacement of coke by high-grade coal (in the form of PCF) is 0.56 for a CGP injection rate of 400 kg/ton and 0.54 for a CGP injection rate of 450 kg/ton. This ratio can be used to evaluate the cost-effectiveness of using low-grade coals instead of high-grade coals. It should be taken into account that additional limestone could be added to the sinter to flux the additional ash, which would make the technology more effective and increase the value of the given ratio to at least 0.65 if the ratio for the contents of nonvolatile carbon in the respective grades of coal has a value of 0.64. Another measure that could make the new technology more effective is keeping blast temperature as high as possible.

On the results of the study was determined the following the benefits of Hot Reducing Gas injection into the blast furnace in comparison with pulverized coal injection:

- Involvement of the low grade coals in the blast furnace operation, including the coals with ash content up to 25%.
- Increase of the amount of injected coals by 2-3 times with adequate coke consumption decrease without problems in the blast furnace raceway.
- Simplification of the coal preparation procedure with involvement of the coarse coals instead of pulverized coals.
- Complete elimination of natural gas with simultaneous increase in a blast temperature up to the maximum acceptable level.
- Intensification of the blast furnace operation and increase of the blast furnace productivity with increase of injected oxygen volume.
- Increase of supply of the blast furnace top gas to the external customers.
- The payback period of capital investments for this technology is estimated in the range of one year.

The technology of HRG injection into blast furnace can be easily implemented at existing plants without any interruption of the production process.

The study by using a multi-zone mathematical model developed by the Institute of Ferrous Metallurgy of the National Academy of Sciences of Ukraine showed that the temperature-concentration and phase fields of the charge and the gas flow in the furnace change under the influence of the same tendencies that are seen with the injection of pulverized-coal fuel (PCF). The fact that the amount of coal which can be injected could be increased significantly by subjecting it to preliminary gasification and fluidizing the ash in tuyere-mounted gasifiers means that the targeted savings of coke could be realized by replacing coke with either high-grade coals (in the form of PCF) or low-grade coals (in the form of CGPs). In this case, for the best variants of the technology (with the addition of more limestone to the sinter) the ratio of the equivalents for the replacement of coke by coal is close to the ratio of the contents of nonvolatile carbon in the high- and low-grade coals (the latter ratio has a value of 0.65 in the present case).

It was shown that the replacement of hot blast by unheated oxygen is advisable if the initial and projected coke and wind rates are both low. If these rates are increased, a changeover to unheated oxygen could destabilize the processes that take place in the furnace and lead to increase the coke rate.

3. PROBLEMS AND PROSPECTS OF COGNITION AND EVOLUTION OF THE BLAST FURNACE SMELTING AS A LARGE SYSTEM

3.1. Phenomenological characteristics of blast-furnace

The principal features

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 of 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 to realisation, if the blast smelting was invented for anew, but not exist in reality. However, the course of blast-furnace smelting in modern aggregates 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. Consider some of the unique properties of the blast furnace, to supply a steady flow of processes at high efficiency, that were formed in the long course of its evolution.

Known two-stage scheme of heat exchange in the blast furnace gives a flexibility smelting technology to changing the modes and provides stability to the process of owls to external influences due to the presence of a “reserve zones”, which soften the heat rejection.

The specified property is inherent in the processes of restoration of oxides, packed bed of coke, changing the state of materials and other. So, in the case of decreasing a melting temperature of materials due to increased content of iron (unreduced material) or decrease basicity the height of the packed bed of coke increases. This helps to increase the residence time of the melt in the packed bed of coke and additional its heat, which partially compensates the underheating materials at receipt in the packed bed. It is also known that the correct selection of the components of the charge contributes to the formation of slag, whose properties (crystallization temperature, viscosity and other little changes persist in the oscillations of the chemical composition (the stable deposits”).

Not continuing the list of the remarkable properties of the processes of blast-furnace, follows pay attention to their orientation: any imbalance of energy, arise-sponding to the in-put or intermediate stages of the smelting, stretched in time and not you-leads the final state of the specified limits. The set of properties, directed on counteraction to external influences, can qualify as a peculiar mechanism of self-regulation, formed a large system “unit-man” during the evolutionary development and accumulation of adaptive traits [13].

Thus, blast fusion - a single organism in which adjoint phenomena of various nature, united by common goals functioning. Properties of this organism include, in addition to the properties of the components, which, as a rule, nonadditive, system properties inherent to the organism in General and created in the course of evolution.

For this reason, attempts to improve the efficiency of the metal by “dismemberment” of the unit into simpler parts - solid-phase (shaft), liquid-phase (hearth) with the expectation of benefits fuel and other not given the positiv results. The expected benefits of these technologies give rise to new problems, solution of which requires additional costs that exceed the potential benefits.

Solid recovery in the shaft furnace is intended to provide high-quality steel from net ores. Due to this, the volume of production of such regulated, and power consumption exceeds a similar amount in mass-howl metallurgy through the use of electricity, the receipt of which requires three-, quadruple cost of primary fuels.

The need to maintain the metalized product from oxidation reduces the scope of its use. The need for high quality expensive metals limited, and the expansion of its production to the scale of mass metallurgy is unprofitable. Release of the same hot gases (1500-1800 gr.C) beyond the limits of technological process cannot be eliminated, and disposal of this heat is only possible at the level of secondary resources at much smaller than in the blast furnace efficiency. Moreover, in PSR extraction of iron cast iron is less, than in the blast furnace process, and difficult-reducing elements almost completely transformed into slag. The process of smelting reduction (PSR) implies the complete replacement of coke and iron-ore raw materials non-coking coal and low-grade raw materials. However, the cots of primary energy in PSR (including energy production in oxygen) exceeds the amount of energy in a traditional sintering and blast-coke-shaft process of the modern technical level [11, 12]. This is due to the exception of technology PSR the most perfect way digestion of heat in shaft contraflow.

Thus, self-contained units, which are, essentially, fragments of blast furnace, have no advantages in the production of mass of metal. Energy, environmental, economic characteristics and integral estimates of low-coke melting surpass characteristics of all known means of direct reception of iron. Coming toward them only COREX process that retains the basic advantages of the blast furnace, as a product of a long evolution.

For these reasons, blast smelting and microwave remain the determining technological module ferrous metallurgy, development of which will form the shape of the whole metallurgical complex. By blowing in tuyeres of hot products coal gasification is possible reduction of coke consumption up to 300 kg/t on most blast furnaces in different conditions and at least up to 200 kg/ton furnaces with low heat requirement. Further evolution of the blast furnace related to the restructuring the processes on full replacement of coke by the products of gasification of low-grade coals. Such development of the blast furnace smelting so strengthens its defining positions in metallurgy, that in the foreseeable future alternative ways not foreseen.

Heterogeneity of processes and the choice of modes

In the practice of blast-furnace production known phenomenon of the ambiguous influence of some parameters on the course of melting and indicators of work of the furnace.

So, the closure of separate groups of tuyeres with less active work of hearth results at the first stage to the enhancement of its activity and improving the indicators of melting. However, over time the run of the heat is gradually deteriorating, coke consumption increases production output reduced. When you open a previously closed tuyeres the processes are again liven up, and improved performance. The frequency of such processes is measured in days and cannot meet the task of long-term stabilizing the heat. More radically on the run of the heat affected by a change in the diameters of all tuyeres, however, has a similar frequency, but the value of her on the order more and is measured in months and more.

Such phenomena inherent in the processes of change of parameters of loading of the furnace, cooling systems, air blast, tapping and at first glance it may seem paradoxical. However, in complex viewed from the positions of to-day melting like a great system they have a common basis to reflect your state of this system.

Traditionally prevailing approach to the analysis of processes of blast-furnace alleged assumed stationary regimes in time and space. Known abstractness of this approach is useful in cognitive terms, since it easier to study the scientific new processes, and justified when analyzing real technologies, running for results of processing the indicators for longer periods of time, during which the role of transient state is small. In the course of this analysis formed the parameters of the pre-individual States sought by the actual technology.

However, the real processes in a blast furnace are distributed unevenly: when updating periphery work of the furnace - inactive centre, the Central course of the gases in the furnace is inactive periphery, have a place to channel the movement of gas, blockage of hearth, education accretion in the shaft, the bosh and the hearth (between tuyeres and below them, etc). In a pillar of a blast furnace burden, thus, there are both high-level and weakly working (stagnant) zone.

Due to the uneven distribution of the environment and its properties in the volume of the unit of each mode contains components that are not consistent with its medium parameters and deforming over time average parameters and indicators of melting by the accumulation of new properties. On this basis, happens in a spontaneous offset the status of the processes in another area that requires adjustment regime to achieve for data indicators. The baseline causes of heterogeneity of processes in the furnace:

- the heterogeneity of composition, properties of the applied charge materials and downloading them on the top;

- heterogeneity of the composition and properties of coke coming in the tuyere source and uneven distribution of blast and blow additives on the circumference of the furnace and in the volume of combustion sources;

- features of the system cooling elements of the furnace;
- local and uneven-periodic character of tapping of the smelting products.

Some of these inhomogeneities are controlled, such that their impact may be adjusted upon entering the furnace. This refers to the composition of charge materials and the way they download on top, some parameters of tuyere stocks and cooling modules furnace, periodicity tapping. However, many properties of iron ore and coke not only not controls invocation, but generally poorly studied; tuyere heterogeneity of processes laid discreteness of the blast stream (limited number of tuyeres) and radial heterogeneity- of peripheral input blast. These factors create an unmanaged component of the processes of melting, which contributes to the drift of parameters and indicators in the area of unintended regimes and the need for adjustments in new unexplored conditions to achieve the required performance.

Reaction of processes of blast-furnace on unsupervised heterogeneity entrance governmental depends not only on the values of these inhomogeneities, but also on the duration of their development and the frequency of occurrence.

Duration of the transient process through various channels is 4 to 30 hours. The high-frequency fluctuations of the parameters, a period of which are by-row is less than the specified time, practically ignored microwave and do not affect the output parameters. Fluctuations commensurate with the time of the transient process of owls, the most significant effect on the current status and should be monitored for use in operational management. Long-term changes, the duration of which exceeds considerably the duration of the transient process, lead to a slow drift processes with access to the new regime.

If in the first case there is no need to track the nature of impacts to manage, then the second requires organization of the operative control of parameters in pace with the process for formation of control actions stabilization the course of melting and outcomes. In the third case, interventions tracking drift processes of melting by special processing of items and indicators for identifying the characteristics of drift and development of new regimes corresponding to the desired end results performance, consumption coke, and the quality of cast iron. As a rule, such analysis is estimated on the basis of non-complete information with the empirical selection of parameters of rational regimes, often by trial and error.

Scientific approach to solving this problem requires functioning automatic system analysis (ASA) performance and processes of blast-furnace with continuous processing of retrospective data, the emission trends, modelling of new meeting this goal regimes and the subsequent realization of the best of them. This would not only expedite the finding of the above-mentioned rational solutions, but also provides a selection of the best of them, according to specified criteria. Solution of this task is aimed at identification of the most effective modes, bring the system to the limit States that diminish its entropy. However, continuous contact with the external environment advance and penetration into the system of random disturbances which form in the process and remove the system from the limiting states leading to the increase of entropy.

Thus, known from the practice of blast-furnace production drift indicators melting during the same mode, and also the maintenance of parameters under the periodical changing the mode and return to it do not contradict the laws of mernostâm functioning of the blast furnace, as a large system. Due distribution of the environment and its properties in the volume of each unit regime keeps the components for its medium parameters and deforming over time average parameters and indicators of melting by the accumulation of new properties, enabling spontaneous shift the status of the processes in a different area and require adjustments to the regime to achieve the targets.

A decrease of the space-time inhomogeneity parameters (due to the stabilization of the composition and properties of the charge and the blast, the uniformity of their distribution of feeding into a microwave, improve designs of units and equipment) is to increase the duration ration of drift up to the values in some casesc made with the overhaul life of work of the unit. Tracking drift to the emergence of the new regime requires the use of an automated system of control and analysis of processes (ASA)

3.2. System analysis of blast-furnace smelting

Blast smelting in General is not a mere collection of individual events, and complex function of their relations, the nature of which is difficult of such phenomena and properties that are not found in a separate phenomena. These features of the processes to-day melting allow us to characterize it as a big system in the modern sense [14], which includes the fundamental concepts:

Integrity and divide. Organization. Integrative quality.

The system is not reduced to a simple combination of elements. Studying the elements of the operation, you cannot know all the properties of the system as a whole. Due to the aforementioned and in studying the metallurgical technologies and their development is based on the ideas systems approach - System analysis.

When studying and generalization of the regularities of blast-furnace found some of the principles inherent in all major events and the process in General. One of such principles relating to the processes of assimilation of heat in the blast furnace formulated by M.A. Pavlov summarizing the position expressed previously by R. Okerman [15, p.436]: “Every cause, reducing heat consumption in the blast furnace process, gives the greater the saving of fuel, the less was the coefficient of thermal in a blast furnace”. This principle implies an important consequence of the lesser efficiency of each subsequent step in the improvement process of assimilation of heat compared with the previous that completely corresponds to the change in the character of heat-exchange processes in the furnace.

Our analysis showed [11, 12], that a temperature increase of blast leads to such change of temperature field of the furnace and thermal conditions, which the efficiency of the blast is reduced. From this analysis follows also that the statement holds true not only for the blast temperature, but also to any other measures affecting the thermal performance of the furnace and its temperature. It was shown [11, 12] that this is true not only for the process absorption of heat, but for all other processes in a blast furnace (heat and mass transfer, gas dynamics and other), which confirmed the known data of theory and practice.

So, increase of the natural gas more efficiently at low amount of reducing agents per unit of oxygen from the charge. If oxygen in the furnace little (for example, if the charge is metallized), and the number of reducers high (high consumption of coke) the efficiency of use of natural gas will be lower. The higher natural gas consumption leads to an increase in the number of reducers per unit of oxygen from the charge the right way and, consequent to a reduction of the efficiency of the subsequent portions of natural gas.

Desulphurization of pig iron blast furnace is required to increase the basicity of the slag. With each subsequent step is improving the basicity less effective in terms of desulfurization than the previous one in connection with the approach of the system to thermodynamic equilibrium decrease in the stability properties of slag with changes in temperature.

Activities contributing to increase the permeability of the upper zone, for example, elimination trifle of agglomerate, the most effective under conditions when the upper zone determines the bandwidth of the charge of gas. As you increase the permeability of the upper zone of defining the area becomes lower part of the furnace and the effectiveness of dropout fines reduced. When gas-permeability of the charge is determined by the lower area the most effective activity contributing to the reduction of the resistance of the post of the charge in the bottom part are becoming increase of durability of coke, selection of rational parameters of air tuyeres, slag mode and others.

Based on the provisions set forth, we can conclude that the changes in processes under external actions are directed at weakening the influence of these effects and in a generalized form we can formulate the principle of Okerman - Pavlov as the PRINCIPLE of DAMPING:

MAXIMUM EFFECT FROM APPLICATION OF EACH MEASURE ON IMPROVEMENT OF BLAST-FURNACE SMELTING IS ACHIEVED UNDER CONDITIONS, THAT OPPOSITE THOSE, TO WHICH LEAD THESE CONDITIONS.

As we approach the regime appropriate to the full realization of this event, its effectiveness at each step of the implementation of reduced.

Each event affects the basic processes in the oven in a different extent. So, heating of blast most strongly affects the thermal processes, consumption of natural gas for reducing and screenings of trivia from charge – on gas dynamics. Various activities can affect the course of the process in different directions.

Because each step in the implementation of a separate event shifts the terms of the processes in the furnace to the side of regimes that further steps will be less effective combination of the event with the other, is in charge of maintaining the offset of the conditions for the processes in the opposite direction increases the efficiency of both events. This allows the selection of such combination qualitative and quantitative support the conditions of development of processes in the furnace at some optimal level realizing the maximum efficiency of the entire set of activities. Such effective combinations are, for example, the injection of hydrocarbon – enrichment of blast oxygen injection of hydrocarbon - increase of blast temperature, leaving trifle of agglomerate – improvement of strength properties of coke elevated levels of iron in agglomerate – decrease of sulfur of the materials brought in the microwave and other. On this basis, we can formulate the PRINCIPLE of combining:

THE MOST EFFECTIVE COMBINATION OF SUCH MEASURES, WHICH AFFECT THE BASIC PROCESSES IN THE FURNACE IN OPPOSITE DIRECTIONS.

This principle should give such a combination of measures, being carried under optimal mode of the blast furnace process lead to the minimum change in this mode.

Considered two principles cover the blast smelting process as simple summation phenomena but do not account for its unity as a large system in which the connections between elements are not less important than the elements themselves and the system includes characteristics not the inherent its individual elements. As the development of such a system a number of complex parameters are close to the limit as independence regardless of influencing factors. In the blast furnace process, in particular, reduces the period of stay materials in the furnace, reduces the amount of gases per unit materials increases the intensity of melt filtration through the packed bed of coke that way to reduce the stability of the flow of the processes and makes it difficult to manage. Formally it is expressed in a decrease in entropy of the system.

SYSTEM APPROACH TO THE BLAST FURNACE PROCESS ALLOWS US TO FORMULATE THE PRINCIPLE OF LIMITING CONDITIONS:

AS TECHNOLOGY IMPROVED, BLAST-FURNACE SMELTING AND PROXIMITY TO SOME LIMIT REGIME EFFICIENCY OF THE ENTIRE SET OF ACTIVITIES FOR FURTHER IMPROVEMENT OF REDUCED.

One of the illustrations of this principle may be widely known in the practice of blast-furnace production provision that when intensive and highly-economical during blast-furnace melting a small deviation from steady state leads to higher losses than in the case of low-productivity and low-economical blast-furnace melting. This is due to stronger influence on indicators of melting time of stay the charge in the furnace as well as complication of the organization gase-division on the cross section at a low specific exit of gases.

Three set out the principle cover the whole set of properties of the blast furnace, as a large system.

3.3. Prospects of further knowledge of blast-furnace processes

As shown earlier [15, 16], the development of the technology of blast-furnace during the whole six centuries period was closely connected with the cognition of regularities of its processes, and in the early 4th century - at the empirical level. 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 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 processes 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 reflect 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 modelling takes a big place. The analysis [14-16] showed 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 and Russian developers [58-60]. 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 require 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 monograph 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 can serve as a basis for the deepening of the conclusions and developing new technological solutions.

Developed in Iron and Steel Institute NAS of Ukraine mathematical model of blast-furnace processes is builded 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.

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.

The study of the influence of the input parameters of the heat on the formation of the temperature-concentration phase fields showed significant quantitative differences for different settings: the most powerful, along with the distribution of materials, was the influence of pre-metallization of the charge, the flow of natural gas, oxygen and temperature blast; other parameters affect weaker. Made analytical researches have allowed to reveal and clarify some of the laws of a course of heat exchange processes and phase transformations in materials, some of which qualitatively confirmed previously conducted experimental studies and can be used to improve technology and further the study of the processes of blast-furnace. The main of them are the following:

1. The presence among the total number of radial ring zones (RRZ) with different character of heat transfer in height, individual RRZ, in which the transformation of a two-stage scheme of heat transfer in the direction of a single-stage. This is due to the inevitable concentration in real conditions the formation of radial and circumferential uneven distribution of materials and gases with the formation of a cross-section of various largest ratio of thermal capacities burden and gas streams elements. Transformation characteristic of two cases:

- at the increase of the ratio of thermal capacities burden and gas streams in the upper zone to a value close to 1, with degeneration of upper secondary heat transfer (for example, deep enrichment of blast oxygen);

- at the reduction of the ratio of thermal capacities burden and gas streams (aspiration to 1) in the lower zone at the expense of reduction of heat consumption for direct recovery and dissociation of carbonates with partial degeneration of the lower step to the heat transfer (for example, when using a pre-metallized raw materials).

2. Minimum development of the direct reduction of iron on the periphery of the most high in the zones with a maximum ore load, sometimes in the centre of the oven. The result is determined by the influence of a complex of factors, including the number of reducing gases ($CO+H_2$) per unit of oxygen furnace charge, the share of solid carbon in the post and height ranges of temperature of the charge >900 °C in this RRZ. The dominant influence of the first factor in the peripheral RRZ defines the strong development of the indirect recovery and weak - direct. In Central RRZ the influence is hampered by the large share of solid carbon in the post and height ranges of temperature of the charge >900 °C.

3. Outflows of gas in the radial direction at different horizons, associated with the change of resistance of layers of the charge and the parameters of a gas stream in the course of filtration through the charge column. The possibility of cross flows is conditioned to the layered structure of the column of charge, in which layers of coke have in 5-6 times more permeability layers of iron ore, and in some areas - on the order and more. While in the lower high-temperature areas VTZ-8-12 through more permeable RRZ low ore load pass more gas (by weight) than less permeable RRZ with high ore load. During the heat transfer in the post of the charge the gas in the first cooled less than secondly, the temperature becomes higher and the volume is greater than that stimulates the flow of gas from the first to the second through coke layers. Such a «feeding» gas tight RRZ through coke layers only partially compensates the imperfection of the heat transfer due to the uneven distribution of materials. Several specific is mechanism overflows in the viscous-plastic zone.

Under this zone is going flow of gas to the periphery and axis and above - reverse flows. The flow of gas flows around the viscous-plastic zone through the «vents».

4. A complex system of direct and backward linkages zone settings softening and melting (SMZ) with the complex input, intermediate and output parameters of blast-furnace melting:

- the location and configuration of SMZ depends on the distribution of materials on the top, their physico-chemical properties and the degree of recovery, the nature of the temperature field of the furnace and the intensity of selection warmth walls;

- settings formed by SMZ influence the distribution of gas flows and basic processes in volume of the furnace, and also on the output parameters of melting and formation of control parameters.

Final values of the parameters educated SMZ depend on the targeted systems management.

5. Organically inherent conic bootable devices (CBD) parabolic distribution of the ore load (OL) characteristic of increased values OL 2 - 3 intermediate RRZ and differs significantly from the distribution OL when loading non-conic (flume) device (NBD) ensuring uniformity and stability OL. This is allowed, on the basis of the above approach, first determine by calculation (using the model forecast) expected reducing coke consumption when using NBD instead of the CBD.

6. A complex system of direct and backward linkages of heat losses through the walls of the furnace with a complex input, intermediate and output parameters of blast-furnace melting:

- the amount of losses depends not only on the design of the refrigeration system, but also to the distribution of materials and gases in the cross-section furnace temperature distribution in the height of the charge and the other

- the obtained value of heat losses through the walls of the furnace substantially influences on the thermal performance of the peripheral zone, the character of heat transfer in it and in the entire furnace and ultimately the consumption of coke for all modes of heat.

End the magnitude of the losses of heat are defined targets to manage.

Identification considered and other possible patterns based on a pre-view of the processes of blast-furnace (BF) in the form of a complex polymorphic temperature-concentration, phase and gas-dynamic fields in the volume of BF, sampled on 120 local volumes (12 in height and 10 radial), which are related to each other in one system of material-heat balance with the identification of limiting local volume. The analysis of processes on such a basis allows avoiding at least a system error inherent in the known approaches. An example of such errors is the use of the forecasts expressions, which contain assumptions about insignificant magnitude of the difference of temperatures of gas and charge on the boundary of two zones of heat transfer (<10 gr.) for furnace as a whole or for use in producing this overestimated values of the coefficient of heat transfer. The essence of the errors in the following.

The basis of the theory of heat exchange in the blast furnace melting laid two-stage scheme of heat exchange in height, is due to the availability in the Central part of the column area of excessive internal heat, which separates the upper zone of intensive heat exchange with the attitude of thermal capacities burden and gas streams mV = (Wш/WR) < 1 from the lower zone of intensive heat exchange with the attitude of thermal capacities burden and gas streams, mn = (Wш/WR) > 1. The main factors of the internal heat of the charge are the development of direct reduction of iron and transformation of carbonates. But as reducing consumption of raw flux level of direct and recovery, as well as increasing the degree of pre-metallization of charge with the decrease in the volume of direct recovery, there is a reduction of the intensity of heat transfer and accordingly increase the difference of temperatures of gas and charge on the boundary of heat exchange with the gradual transformation inherent in the blast furnace melting schemes of heat transfer in the direction of the scheme, the inherent cupola. Forecasting the efficiency of the use of pre-metallized raw materials with the help of a model in which this is not taken into account and postulated the difference between the temperature of the gas and the charge on the boundary of two zones of heat exchange <10° to the furnace in General, gives a distorted results [31], that in the analysis of this factor can be seen more clearly than other factors.

The revealed regularities of transformation of temperature and concentration, phase and gas-dynamic fields in the volume of the BF and transverse cross-flows of gas for high column of charge help to explain a number of complex phenomena (see above) and can be considered as self-regulatory tools in a large system «Blast smelting».

The installed complex system of forward and backward linkages zone settings softening and melting (item 4), as well as the loss of heat through the wall (item 5) with the complex input, intermediate and output parameters of the blast-furnace smelting is an important component of the system analysis of the smelting.

Further study of this system considered method with the addition of new experimental research identifies new regularities of the development processes and its additional system properties.

3.4. The problem of complete substitution of coke and restructuring on blast melting technology without coke (Coke-less technology)

Blast smelting is a single organism whose properties include not only the properties of the component parts, but also the system properties inherent to the organism in General and created in the course of evolution. For this reason, attempts to improve the efficiency of the metal by "dismemberment" of the unit into simpler parts – solid-phase (shaft), liquid-phase (hearth) with the expectation of the advantages of using fuel produced no positive results [15, 16]. The expected benefits of these technologies give rise to new problems, solution of which requires additional costs that exceed the potential benefits. Technology of solid-phase reducing in the shaft furnace envisages preservation of the metallized product from oxidation and is designed for receiving high-quality steel from net ores. Due to this, the volume of production of this metal regulated, and power consumption exceeds a similar amount in mass metallurgy. In the process of smelting reduction (PSR) costs of primary energy also exceeds the amount of energy in a traditional sintering and blast-coke process of the modern technical level [5, 6]. Energy, environmental, economic characteristics and integral estimates of blast-furnace smelting with low coke surpass characteristics of all known means of direct reception of iron. Nearer than other toward them is COREX process that retains the basic advantages of the blast furnace, as a product of a long evolution.

Thus, blast smelting remain the determining technological module ferrous metallurgy, development of which will form the shape of the whole metallurgical complex. By blowing in tuyere sources of the dust of low-ash coals up to 250 kg/t or an equivalent amount of hot products of gasification of high-ash coal possible reduction of coke consumption in different conditions up to 200 - 250 kg/t, by best conditions 180-200 kg/t. The Further evolution of the blast furnace technology is related to its restructuring on coke-less process with full replacement of coke by products of gasification of low-grade coal [15, 61].

Analyzing the origins and development of metallurgy without coke, we came to a conclusion about the regularity to obtaining of iron without coke in the evolution of the blast-furnace smelting and proposed technology and the unit to meet the basic ideas, which developed D.K. Chernov [32] – shaft-hearth unit (SHU). Follow-up work in this direction, taking into account the experience of industrially developed COREX process enabled to give the proposals set out below in relation the technology without coke to one blast furnace of combinate “Zaporizhstal” [33].

Blast melting technology without coke – TWC (Coke-less technology - CLT)

Constructive decisions

Blast furnace useful volume 960 m^3 rebuilt in shaft-hearth unit (SHU) and technology without coke (TWC) on the basis of blowing the hearth hot products coal gasification (PCG), generated in installed around the blast furnace hearth on tuyeres reactors gasifiers (TRG). SHU (Fig. 3.1, General view) consists of shaft 1, bosh 2, hearth 3 with hearth-roof 4. The angle of the bosh to the horizon > 60°. The shaft and hearth are separated by a solid partition, which for the shaft is the bottom, and for the hearth - the roof. The roof is executed not flat, but in a circular folds. Top edge (combs) of these folds level or close to the horizon. Lower ribs (depression) have the slope to the periphery. The side faces of the folds in a vertical cylindrical section of the form of “saw”. The slope of the valleys and side faces to the horizon of approximately corresponds to the angle of repose of the materials. A folded vault relies on the bosh, reinforced by backup ring. Bosh are separated by folds of the root at triangles belonging alternately to shaft and hearth. This configuration roof allows to:

- create a rigid structure for the perception of the load of the material in the shaft;

- the most economical use the height of the blast furnace.

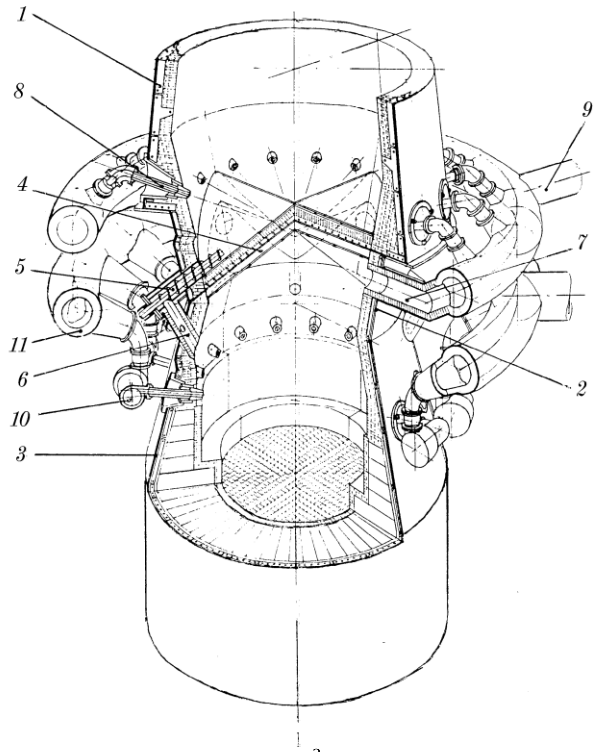

Figure 3.1. Blast furnace useful volume 960 m^3 rebuilt in shaft-hearth unit (SHU)

Along the edges of the depressions of the roof in the wall of the bosh installed screw loaders charge 5 with unloading chutes 6, according to which material from the shaft to be overloaded in the hearth. Axis screw loaders are installed along the radii and at the same angle to the horizon, and ribs depressions that allows you, firstly, to ensure unimpeded gathering of granular material and, secondly, ensure that the axis of the screw in vertical plane below the verge ring pipe hot blast that will be necessary for the smooth replacement of the screw. The number of folds arch divisible by the number of lances hearth (for example, 4 or 6 at 12 tuyeres).

Such design of the bottom of the shaft, in combination with regulated by the number of tuyeres of the screw loaders, provides smooth and controlled re-load materials from the shaft into the hearth. Under the ridges of the roof, in the wall of the bosh, is situated hole flue 7 hearth gas.

Vents are connected circular pipe with 8 nozzles for the tuyeres of shaft. Thus, a furnace attendant, gas is supplied from the forge to the shaft. From the ring pipe for hearth gas a diversion 9 on recycling system that allows you to regularly monitor the amount of feed into the shaft gas.

Lance shaft are evenly spaced around the circumference in places of the greatest loosening material (0,5-3,5 caliber lance).

The cooled gas recirculation system (gas furnace attendant with its excess or peeled top pile) is served in the hearth through the mating screw loaders. Together with this gas in the hearth served fluxes and additives. The hearth SHU has a cylindrical part, repeating a casing of blast furnace, conical tuyere zone, which is adjoined bosh and roof.

By the circumference of tuyere zone on each tuyere are situated reactors-gasifiers (TRG) 10 (Fig. 3.1, 3.2), connected to the ring pipe of hot blast 11. To TRG summed up the line of the crushed coal and oxygen. The tuyeres are tilted toward the horizon at an angle 10-20 gr.

Thus, the design of the SHU differs from blast-furnace some change of the geometrical sizes of tuyere zone and bosh, as well as the presence of the arch of the hearth. Cooling shroud the hearth of tuyere zone, bosh and shaft is performed using cast iron cooling refrigerators and conventional cooling systems. Cooling of the roof can be accomplished by setting coils, stacked on the verge of the arch side of the shaft, with filling of space between the pipes of the coil heat conducting putty. Refractory lining of mine traditionally solved, and you can expect a significantly better resistance to this lining, as in the shaft SHU there are no zones of high temperatures (the gas in the shaft is not higher than 900 °C.

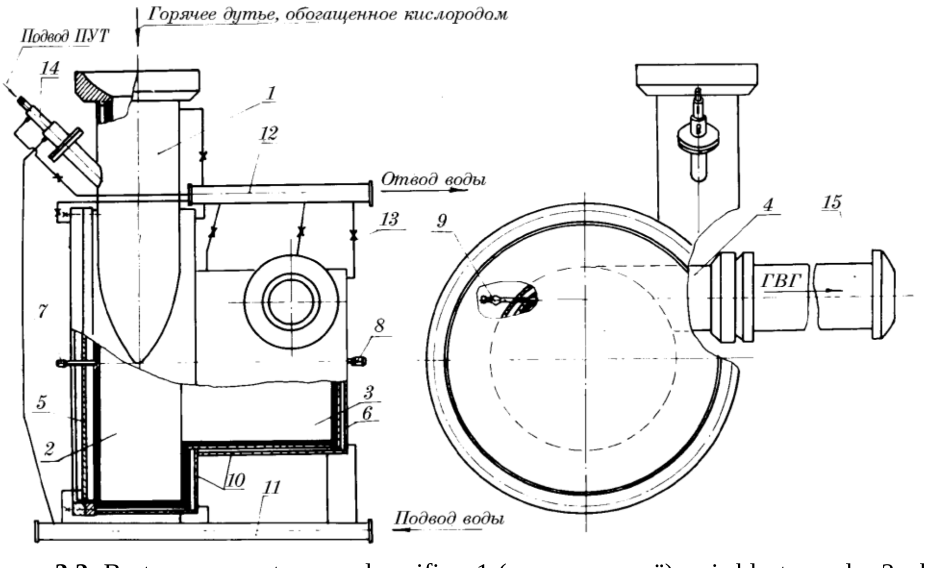

Figure 3.2. By-tuyeres reactor - coal gasifier: 1 (горячее дутьё) - air-blast supply, 2 - big camera, 3 - small camera, 4 (ГВГ) - transport of hot reducing gas (HRG), 5 - cover, 6 - the wall of the chamber, 7 - in temperature sensor, 8 - sampling gas, 9 - peep-hole, 10 - water-cooling, 11 - collector supply water, 12 - collector of water drainage, 13 - gates, 14 (ПУТ) - tuyere filing he crushed coal, 15 - blast nozzle

Lining of the bosh, tuyere zone, hearth and bottom also does not differ from traditional solutions. Lining of the roof should be done with both of shaft and from the side of the hearth. From the side of shaft this can be fireclay lining, fits on top of the cooling coils, and covered with a protective plates of wear-resistant cast iron, and from the side of the roof, is probably the most suitable lining with refractory concrete, pour between the housing code and protective suspended slabs. Can be treated the same lining outboard arch brick.

Charging iron-containing materials on the top is done in the same way and using the same equipment that are in conventional blast furnace. To improve gas dynamics concentration in the shaft is desirable to consider the screening trivia 0-5 mm before downloading of agglomerate skip. On Fig.3.3 provides vertical sections of the unit.

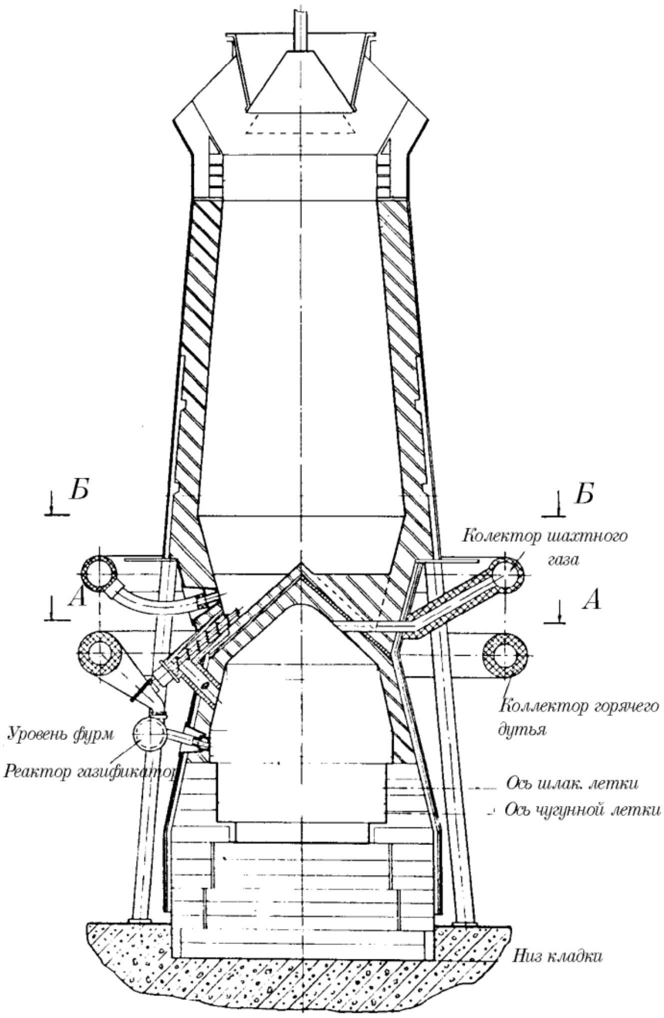

Figure 3.3. Vertical incision of shaft-hearth unit (SHU): *Коллектор шахтного газа* – **Collector of shaft gas**; *Коллектор горячего дутья* – **Collector of hot blast**; *Реактор – газификатор* – **Reactor-gasifier**; *Ось шлаковой летки* – **Axis slag taphole**; *Ось чугунной летки* - **Axis cast iron taphole**; *Низ кладки* - **Bottom masonry**

Furnace operation

On Fig.3.4 shows the anticipated distribution and movement of the material in the shaft-hearth unit (SHU). When lowered into the shaft and the bosh of the restoration of the iron oxides blowing in shaft reducing gas to the degree of metallization 75-85 % at gas temperatures up to 900 °C, with under which remains solid-state materials. The maximum temperature in the mine, which is fully preserved granular solid state materials, established on the basis of laboratory studies.

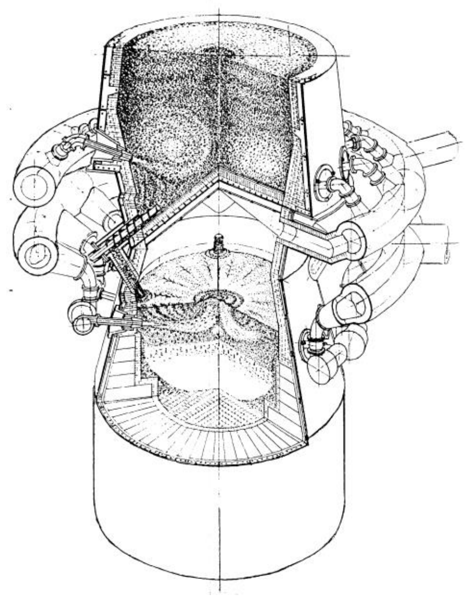

Figure 3.4. Estimated distribution and movement the material in the shaft-hearth unit (SHU)

The recovered material is reloaded into the horn screw loaders with adjustable speed overload. In each of the 12 TRG installed in circumference of hearth comes hot oxygen-enriched blast and crushed coal. The volume of the TRG happens coal gasification with liquation ash.

Products of coal gasification (PCG) with the temperature of 2200-2500 °C come with a layer sintered materials, onto the surface of the melt in the furnace. In the layer is melting materials, post reduction oxides and partial carbonization of metal due to the excess of solid carbon contained in the PCG. In the cylindrical part of hearth happens separation melt metal and slag with periodic release them through the notch.

Hot reducing gas (HRG), rising in roof part of hearth mixes with the cold reducing gas (CRG), blowing in this area for the temperature not more than the beginning of a softening materials - 900 °C.

The gas enters the collector and from collector - to shaft and partly in gas cooling to ensure CRG. A distinctive feature of hearth HGU, as already mentioned, is that, in contrast to the blast furnace, the hearth is separated from the shaft roof. Material in the furnace hearth entire volume between the surface of the material and the roof is free, filled with gas, space, that leads to the formation in the furnace over a layer of liquid pig-iron and slag fluidized bed materials which, with its fluidizated layer high rates of heat and mass transfer, heats the incoming material, its melting and reducing reactions as indirect and direct nature.

To ensure the possibility of such work furnace ore chutes introduced in the hearth through the walls of tuyere zone at low altitude above the surface of the material. This method of input material in the hearth provides the exception of crossing jets sack material flow departing from hearth gas that otherwise would have led to the active removed from the hearth in the shaft, fine fraction of the material and would impede the work of the shaft.

Vents are located in the higher points of the walls of the hearth under the ceiling of the folds of the roof. Thanks to this movement of gas in the furnace is formed in the following way: gas layer of material goes in the Central part of hearth due to the nature of the movement of tuyere jets in the layer. This Central pillar of gas goes up, the roof and is divided into sleeves to vents, but in the space between these cent-General post, ceilings and walls of the hearth, there is inevitably a torus-like vortex flow, in which the motion of the gas occurs from the center up to the periphery of the arch - down along the walls of the hearth - to the center above the layer of the material.

The dust particles in this whirlwind acquire the centrifugal force directed to the roof, the walls and the surface of the material.

Coming out of the layer HRG has a temperature of 1200-1300 ^{O}C. In these conditions, dustable ore particles very quickly heat up, restored, colliding by in a turbulent flow, coagulated, the required speed of their airborne increases due to the growth of size and density, and increasing with the growth of the mass of the particles centrifugal force knocking them to the periphery of the flow on the walls and the surface of the material. Thus, one can imagine the mechanism of a kind of thermal-chemical separation of the passing of hearth the gas flow from the dust particles. Education fluidized bed materials in the furnace confirmed by the available research jet fluidization [34]. The presence of the fluidized bed in the furnace noted by the authors of the COREX technology [35].

The essence of a jet of fluidization is that [35, p.10] hydraulic forces lead to a change in the stress state in the layer. The forces of internal friction and adhesion of particles decreases in the local conical volume of the layer under the influence of tangential shear stresses there is a sliding particles relative to each other, and appear closed circulations (vortices), formed by a movable particles between rarefied Central part of the jet (torch) and peripheral region (layer). The diameter of the active zone with the vortex motion of the particles exceeds two or more times the diameter of the torch. Flame dimensions increase with the initial impulse of a jet and a reduction of the size and density of particles.

At the dependences given in the work [37], made an approximate calculations which showed that by the options of tuyere gas and the diameter of the nozzle 150-200 mm horizontal range jets will be 3-3,5 m, which corresponds to the radius of hearth SHU on the basis of blast furnace displacement 960 m^3 and, thus ensuring the active processing of the material in the center of hearth.

It should be noted that hydrodynamics and heat - mass transfer in fluidized bed in the furnace SHU have distinctive features in comparison with the described in the literature and they have to be studied. There are other mechanisms of movement of materials and gases, providing course of heat - mass transfer processes in the furnace.

The basic technological parameters

Calculation of process parameters TWC in SHU performed by the method developed in Iron and Steel Institute NAS of Ukraine. The methodology of identification of consumption of coal, blast and other resources, as well as the determination of the number, composition and gas parameters based on Autonomous material and thermal balances of shaft, hearth, gasifiers and combined material-heat balance of the unit.

As initial data taken compositions of iron-containing raw materials and coal, as well as process parameters, characteristic for the "Zaporizhstal".

For charging on the top used lump iron-containing raw materials of sinter, pellets, iron ore. Size pieces 5-50 mm. Fraction 0-5 mm separated before loading in a skip. Composition of the charge is selected based on the maximum fluxing.

On the stage of development of the technologies used the burden of 100 % fluxid sinter and pellets, iron ore and limestone served as additives to adjust basicity.

As additives are periodically metal-additives and lump coal (5-50 mm).

Indicative chemical composition of materials (%):

Materials	Fe	FeO	SiO_2	CaO	MgO	Al_20_3	MnO	S	P
Agglomerate	55,0	12,0	9,2	10,7	0,8	1,0	0,1	0,05	0,02
Iron ore	54,5	2,0	19,0	0,4	0,2	0,5	0,1	0,02	0,01
Limestone	0,5		1,5	53,0	0,7	0,8		0,10	0,01

In by-tuyere gasifiers injected crushed coal. Used coal concentrate 0-3 mm fraction, dried to a moisture content of 1 %.

The possibility of using concentrates with higher humidity is determined conditions of transportation and storage and will be refined in the course of the study. Perhaps the use of coal of different brands, for example, concentrates from the seashore and coal gas, the composition of the working masses which after drying (%) is given below:

Concentrate of coal	C^p	H^p	O^p	N^p	S^p	W^p	A^p
Skinny	81,5	3,0	3,0	1,5	2,0	1,0	8,0
Gas	75,3	5,0	7,5	1,7	1,5	1,0	8,0

Fluxes, as well as iron supplements and other supplements, including flue dust, served in the hearth furnaces in the region transshipment nodes materials from the mine into the hearth. The filing is made by the injection of powdered materials of particle size 0-3 mm.

Parameters of the projected indicators of melting:

The temperature of the charge when loading in shaft – 250 °C.

Temperature of charge by the overload from the shaft in the hearth - 870 °C

The temperature of the top gas - 400 °C

Gas temperature at the inlet into the shaft - 900 ^{o}C

The loss of heat of cooling shaft - 8 % of the needs of warmth.

Removal of blast furnace dust - 30 kg/t.

The degree of metallization of iron in the shaft - 80 %.

The composition of iron on the stage of development (%): Si - 0,5; Mn - 0,1-0,2; C - 4,0; S-0.03; P - 0,05.

The temperature of the metal and slag – 1500^{o}C.

It is expected to receive final results:

Metal composition: Si - 0,2; Mn - 0,1; C - 4,0; S Of 0.03; P - 0,05.

The temperature of the metal and slag – 1550^{o}C.

The loss of heat to the cooling of the furnace - 7 % of the enthalpy of gas at the inlet of the hearth, which corresponds to 10 % for the whole of the furnace.

The temperature of the gas, rather than cooling (recycling)- 900^{o}C; injecting in the hearth after cooling – 50^{o}C.

The temperature at the blast – 1000^{o}C; the content of oxygen- 50 %; humidity- 1 %.

Heat loss with cooling gasifiers - 10 %.

The results of calculation of indicators of melting are given in table 3.1.

Table 3.1. The results of calculation indicators of metal smelting

Indicators	**Dimension**	**Values**
Annual Fund of working time	day	357
Productivity	t/day	2000
Productivity	thousand t/year	714
Material consumption: sinter	kg/t met.	1821
coal (0-3 мм)	kg/t met.	658
including carbon	kg/t met.	517
limestone (0-3 mm)	kg/t met.	67
The number of slag	kg/t met.	490
Parameters of the blast: quantity	m3/t met.	821
the pressure	KPa	200
temperature	°C	1000
humidity	%	1,0
oxygen content	%	40,0
Consumption of oxygen: in the blast	m^3/t met.	211
in the gasifier	m^3/t met.	111
just	m^3/t met.	322
Number of HRG coming out of the TRG	m^3/t met.	1442
Temperature HRG of lances	°C	2313
The total number of hearth gas	m^3/t met.	1579
The number of return gas	m^3/t met.	922
The same in % to the hearth gas	%	58,4
Including marketable gas	m^3/t met.	312
Indicators	Dimension	Values
Contents: CO	%	29,1 (60,6)
CO_2	%	32,4 (0,9)

H_2	%	5,8 (12,0)
H_2O	%	6,2
N_2	%	26,5 (26,5)
Calorific value (moist.)	Kj/m^3	4306
the same dry	Kj/m^3	4573 (8959)
Content in metal: Si	%	0,5
Mn	%	0,1-0,2
S	%	0,03
C	%	4,0
Content in slag: SiO_2	%	37,0
Al_2O_3	%	6,5
CaO	%	46,3
MgO	%	3,3
MnO	%	0,1
FeO	%	0,4
S	%	2,4

Assembly systems

Complex unit on the implementation of the technology of living wage includes, in addition to the ovens, the following systems, which are available on the blast furnace and are suitable for use after adjustment on cokeless technology (technology IWC): removal system and cleaning of the top gas; the system of delivery iron ore raw material (it is advisable to have screenings trifle of agglomerate fraction 0-5 mm.); the system of heating and supply air.

The new systems are included in the complex are:

System of coal transport (Fig.3.5). For the reception and storage of the operational reserve of coal uses existing bunker on the trestle and ore yard. Bunkers, equipped conveyor tract, coal in the initial condition is served on site screening and drying (rumble in combination with air-separation of hot air “pipe-dryer”), from which dried coal 0-3 mm fraction unloaded in the silo. As silo can be used housing released 4th heater. Under the silo is placed distribution and dosing system for the filing of pneumatic transport of the granular coal by tuyere reactors-gasifiers. The TRG developed Iron and Steel Institute NAS of Ukraine, Institute of high temperatures of RAS and AK “Tulachermet” and tested on the stand in AK “Tulachermet” [15, 16].

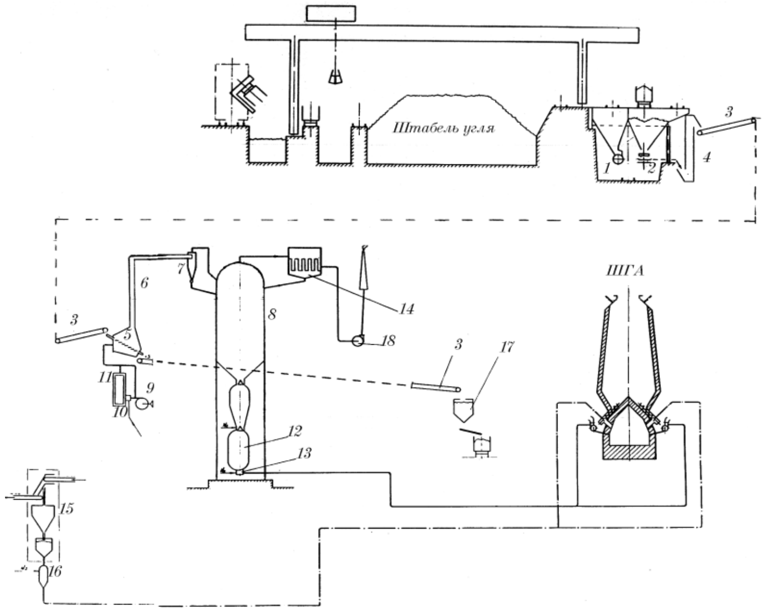

Figure 3.5. Scheme of receiving, training and the supply of coal and flux in SHU:1 - additional equipping of bins, 2 - feeder, 3 - belt conveyor, 4 - Elevator bucket, 5 - classifier, 6 - pipe-dryer, 7 - cyclone, 8 - silo dry coal 0-3 mm, 9 - fan, 10 - burner, 11 - a combustion chamber, 12 - feeder, 13 - dosing, 14 - bag filter, 15 - bunker limestone 0-3 mm, 16 - pneumatic chamber pump limestone, 17 - bunker coal +3 mm, 18 – exhauster

Recirculation system of hearth gas (Fig.3.6). Additional system. Part of hearth gas (see table 3.1) from the ring collector is given in recirculation circuit, consisting of a dust collector, Venturi tubes with droplet separator, throttle group. Cleaned and cooled gas supercharger is served in the hearth mixing with furnacemen on gas. The excess of the cooled gas is discharged into the shop collector of blast furnace gas. Possible mode in which the gas recycle contour of cooling gas will not be enough. Then the missing quantity of cold gas can be substituted by purified top gas. Excess heat hearth gas planned for recycling, can be used for heating air and gas filed for heating stoves with a corresponding reduction of their number. For this purpose in the body of the dust collector can be installed surface of heating of intermediate heat carrier (steam). Experience of such devices is available on the waste heat boilers of open-hearth furnaces and converters.

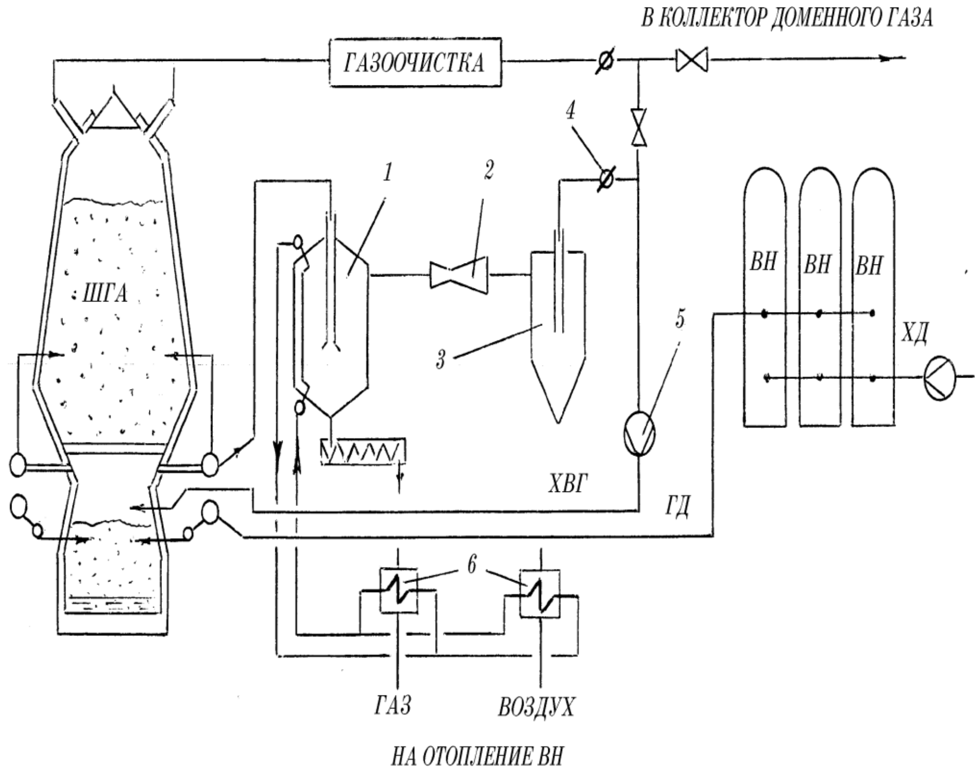

Figure 3.6. Energy-technological scheme of the complex IWC: 1 - hot dust collector with waste-heat boiler; 2 - pipe of the Venturi; 3 - droplet separator; 4 - throttle group; 5 - compressor (compressor); 6 - heat exchangers; ВН - air heaters; ХД, ГД - cold and hot blast, respectively; ХВГ - cold reduction gas; ГАЗООЧИСТКА - GAS CLEANING ; В КОЛЛЕКТОР ДОМЕННОГО ГАЗА – TO COLLECTOR OF TOP GAS; ГАЗ - GAS; ВОЗДУХ - AIR; ШГА – SHU

Assessment of new technology

The basis for comparison of the developed technology with the blast smelting accepted indicators of work of a blast furnace №1 "Zaporizhstal" in December 1997 with the consumption of metallurgical coke (wet) - 598 kg/t, skip (wet) - 543 kg/t, skip (dry) - 517 kg/tons, natural gas - 97 m^3/t, oxygen - 81 m^3/t, blast air and furnace gas - 1270 and 1915 m^3/t, respectively. Instead of coke in the new technology uses a coal concentrate - 658 kg/t (dry), or at a humidity of the original 10 % - 731 kg/t.

Evaluation is performed by changing the components of the technology, the main of which are the costs of coke and coal, natural gas and oxygen blast and top gas.

Fuel and energy evaluation is performed with the use of equivalents of the penal fuel (FE), resulted in works [15, 16, 33].

Consumption of conditional fuel equivalent (CFE) in the BF and SHU (kg/t):

The components of costs	**CFE**	**BF**	**SHU**
Coke (dry)	1,40	724	-
Coal concentrate	1,12	-	737
Agglomerate	0,20	364	364
Limestone	0,015	1	1
Natural gas	1,30	126	-
Oxygen	0,25	20	80
Heating and compression blast	0,115	146	95
Just conditional fuel		1381	1277
Secondary resources		383	282
including coke oven gas		133	-
blast furnace gas		250	282
Consumption process		998	995

These data show that the total consumption of CFE at new technology significantly lower than in the same conditions in BF. The consumption processes taking into account the utilization of coke oven and blast-furnace gases is of the same order.

Environmental assessment is based on the work [36] the values of emissions of owls in coke production. Specific values on 1 ton of coke composition-ranges: dust - 2.66 kg, gas - 7600 m^3, harmful substances of 4.07 kg. In preparing coal gasification gas emissions are taken 3.7 m^3/kg, dust-0.2 kg/t. Per 1 ton of metal emissions from coal preparation are: dust -146 g, gas - 2705 m^3.

Reducing emissions from coke (per 1 ton of metal): dust - 1,59 kg, gas - 4545 m^3, harmful substances is 2.43 kg. The total reduction of emissions: dust - 1.44 kg/t, gas - 1840 m^3/t, of harmful substances is 2.43 kg/t.

In the manufacture of metal 714000 t/year, the annual emission reductions will be: dust – 1028 t, gas - 1.3 billion m^3, of harmful substances – 1735 t.

Economic evaluation is performed by changing the components of the most significant costs, which account (UAH /t metal):

Names of resources and units	BF			TWC		
	Consumpt. per 1 ton	price, UAH	cost, UAH/t	Consumpt. per 1 ton	price, UAH	cost, UAH/t
coke (own), t	0,543	176,3	95,7	-	-	-
coal (own. 8 %), t	-	-	-	0,710	60,0	42,6
natural gas, thousand m^3	0,097	156,2	15,2	-	-	-
oxygen, thousand m^3	0,081	78,5	6,4	0,322	78,5	25,3
blast, thousand m^3	1,270	5,1	6,5	0,821	5,1	4,2
Total			123,80			72,10

The cost of by-products identified by the estimated number of furnace gas in the variants of the BF and the TWC at the price for 1000 m^3 of 14.6 UAH for superior calorific value 3817 Kj/m^3 (estimated for the BF). Cost furnace gas and commodity hearth gas TWC determined in accordance with calorific value (4306 and 8959 Kj/m^3, respectively). In both cases, the share of marketable gas took 0,7. As a result of the cost of by-product credits amounted to:

- furnace gas BF: 1,915·14,6·0,7=19,6 UAH/t;
- furnace gas TWC: 1,267·14,6·0,7·4306/387=14,6 UAH/t met.
- commodity hearth gas TWC: 0,312·14,6·0,7·8959/3817=7,5UAH/t.

Thus, the cost of changing resources less side energy will be:

for BF 123,8-19,6=104,2 UAH/t; for TWC 72,1-14,6-7,5=50,0 grn/t.

Saving the transition to a new technology 54,2 UAH/t metal, and in annual scale in production of 714000 t/year - 38.7 million UAH.

Expenses for re-equipment of BF in TWC and construction devices of preparation and supply of coal, evaluated from available analogues, will amount to 30-40 million UAH, so that the payback period of about 1 year.

The expected advantage of the offered technology TWC in SHU is also the possibility of regulation of the composition of metal (pig iron from 4.5 % to carbon steel with 1-2 % of carbon), which may positively affect the character of the further repartition.

Study of the processes of ironmaking technology without coke (TWC)

To study of processes of new technology and analysis of the modes of its operation was performed a complex of researches [15, 16], that indicate the following:

1. Simulation of the solid phase of recovery in the shaft: by the baseline conditions the material arrives in the hearth SHU with a degree of reducing and metallization greater than in the area of softening and melting of the blast furnace; this means that the consumption of heat and reducing materials in the furnace SHU significantly less than at the bottom of the blast furnace.

2. The study of the “flowability” of agglomerate during the restore process was realization for studying the process of softening materials to preservation of the solid phase in the shaft. For sinter “Zaporizhstal” basicity of 1.3 border loss "flowability" it was temperature of 900 gr.C.

3. The study of the transformations of materials in the slag bath undertaken to assess the impact of the properties of the materials coming from the shaft, on course of the processes in the furnace SHU. Unreduced iron oxides remain in the slag and increase its aggression in relation to the masonry. Admission to slag well-reduced sinter provides already for 120 seconds reducing the content of FeO almost to zero, while for pellet it does not fall below 8-10%.

Analytical study of the processes and the choice of the rational technology

The technique of research is developed at the Institute of ferrous metallurgy and includes a quantitative description of processes in shaft-hearth unit and numerical study of the expected results of the heat balances and energy flows [15, 16].

The results are following:

The most significant advantages iron-making technology in without coke (TWC) are expressed in terms of value: the price of fuel in option SHU-60 less than in BF on 21-23 %, and less than in the COREX on 6-8 %.

When existing conditions charge of the "Zaporizhstal" minimum fuel consumption in SHU corresponds regime of blast with the maximum possible on the conditions of service of the air heaters of blast temperature at maintenance of oxygen in the blast 55-60 %; in the case of the rich, fully fluxed burden minimal fuel consumption is also achieved when the maximum possible value of the temperature of the blast, but at a lower content of oxygen (50-55 %).

The main advantages of technologies without coke are significantly lower cost of fuel (about 20 %) and the exclusion of harmful emissions from coke production.

Industrially developed COREX process allows to solve the economic and environmental problems, however, requires for its implementation the large non-recurring costs for the construction of a new complex. SHU, with the cost of fuel on 21-23 % less than in the BF, and 6-8 % less than in COREX, can be constructed during the overhaul and reconstruction of the blast furnace at little additional cost. Another advantage SHU can be adjustable composition of metal (pig iron from 4.5 % to carbon steel semi-1.5-2 % carbon).

As a product of natural evolution of blast-furnace, iron-making technology in SHU can be organized at the existing enterprises in the course of reconstruction of blast furnaces in periods of regular capital repairs. This uses the existing infrastructure of production and the main part of the equipment. This approach to the restructuring of the steel industry of new technology without conflict solves the main socio-structural problems of the industry and the enterprises, which is not a less significant positive factor, than all the others.

Thus, the evolution of the blast furnace smelting is going on the path of reducing the coke consumption as energy savings, and by substitution of coke less scarce fuel. Development of technology of pulverized coal injection (PCI) with submission in the blast furnace up to 250 kg/tm PCI of low-ash coal and technology injection of an equivalent amount of gasification products of high-ash coals with the General improvement of the technological mode and quality of charge allow to hope for achievement of coke consumption 180 – 200 kg/tm. Further evolution of the blast furnace, related to the restructuring of the technology and design for the purpose of transition to obtaining metal without coke. The regularity of this course of development are conditioned to the specific properties of the blast furnace smelting as a large system and further developments of the works, that was begin by D.K. Chernov.

The results of developments showed that the major advantage of the technology without coke (TWC) in SHU is less cost of fuel and is missing emissions from coke production. Further, the structure of the metal may be adjustable from cast iron (4,5%), to steel (1,5-2%).

As a product of natural evolution of the blast furnace smelting the technology without coke in the SHU (with the cost of fuel on 21-23 % less than in the BF, and 6-8 % less than in COREX) can be organized at the existing enterprises in the framework of reconstruction of blast furnace with the term of payback of less than

1 year. This approach to industrial restructuring without conflict solves the main socio-structural problems of the industry and the enterprises which is not less significant positive factor than all the rest.

3.5. Alternatives of evolutionary progressing of the technology

During the evolutionary development of the blast-furnace smelting technology modernization and improvement of the structure of the unit (blast furnace) was aimed at enhancing the efficiency of smelting iron mass purpose. Other functions are performed simultaneously and, as a rule, does not significantly affect the production targets. However, the blast furnaces has long been the successfully producers of cast ferro-alloys and high alumina slag to produce cement, also the heating gas for power aggregates just metallurgical complex (binds the whole energy into one complex). The force of the blast-furnace smelting technology and design of blast furnace adapted to perform these functions, as well as some other, fundamentally possible under the terms of the functioning of the technology and the equipment. So, manufacture of pig-iron from complex ores containing manganese, titanium, chromium, vanadium, copper, arsenic, rare earth metals, the number of which currently not controlled, can be translated into the mainstream of a managed process with maximum recovery of useful components.

Along with the expansion and improvement of smelting ferro-electric furnaces [37, 38] production of carbon ferromanganese in blast furnaces continues, but the technology has not improved. The ways and methods of self-development of smelting in the blast furnace ferromanganese known and continue to be developed [38-49], and reserves to reduce coke consumption and increase performance quite large. With increasing temperature of the blast from 200-300 ^{O}C to the current level and enriching it with oxygen, possible to reduction of coke consumption. According to some estimates coke consumption can be reduced from the level of 2000 to 1000-1500 kg/ton of the alloy. When assessing the 1 kg of coke to 1,4 kg of conditional fuel subject to supplementary oxygen is independent of the conditional fuel values in the range of 1500-2200 kg/ton of the alloy. With the consumption of coke in an electric furnace 400-500 kg and electricity 3-4 MWh per tonne ferromanganese consumption of fuel equivalent (in equivalent to 1 kW hour - 0.4 kg srvc. fuel) will amount approximately to the same extent. However, blast furnace, except ferromanganese, produces commercial energy in the form of-furnace gas, the quantity of which amounts to 30-50 % of the consumed, and the production of coke formed coke oven gas (450 m^3/t of coke), which provides a significant part of the needs of the enterprise. The question about the use of off-gases furnaces remains unresolved. Thus, the energy efficiency of smelting in the blast furnace ferromanganese higher than in electric furnaces. Above the degree of extraction of manganese alloy (80-85 % versus 70-75 %). These fundamental preconditions are the basis for the transfer of smelting the main part of the carbon ferromanganese in blast furnaces.

Similar conditions determine the feasibility of smelting in the blast furnaces of ferrochrome. Fundamentally this task is solved in the early 40-ies in the Urals [50-53]. Developing the technology of M.M. Mikhailov [50] substantiated the application of oxygen-enriched air and showed high effectiveness of such technology, due to the movement of high-temperature fields in the lower horizons of the furnace, where the main heat consuming processes.

One of the major directions of development of blast-furnace processing is titanomagnetites with the receipt of vanadium and titanium containing cast irons and using the Converter slag to obtain ferrovanadium and other products [54, 55]. We know the experience of smelting in the blast furnaces of ferruginous bauxite high alumina slag (up to 50 % Al_2O_3) for the production of rapidly hardening cement and simultaneous melting cast iron, which has a higher wear resistance. In [56] the possibility of using the melting of bauxite as the first stage of obtaining alumina followed by leaching. Suggested the possibility of production of aluminum alloy.

Set out the functions of the blast furnace together with the main one - smelting blast furnace and cast iron are metallurgical, whose main task is manufacture of metal and slag.

Implementation of these functions under any of the target plant is accompanied by the production of gaseous fuel - furnace gas, so that in all conditions blast furnace is a critical power unit of the metallurgical complex. In Ferroalloy production, and waste quantity and the calorific value of the top gas per unit of production is significantly higher than in the case of pig iron, so that the energy component of the melting more.

It is characteristic that the evolution of the main production - smelting pig-iron on the path of reducing fuel consumption and level of its use in the furnace, in accordance with decrease in the number and the calorific value of the top gas. At the same time increases performance units, this leads to the release of capacities. In these conditions the use of blast furnaces to perform other functions, particularly energy, becomes a natural direction of development of metallurgy. The development of the energy function is seen in two directions:

- autonomous of production technology of rehabilitation and heating gases by means of a transfer of separate blast furnaces in the mode of gas generators on the basis of non-coked coals;

- organization of production of ferroalloys and special toxins in blast furnaces, in which the energy component of the technology increases by increasing the heating value and quantity of gas per unit of alloy.

In a particular company solution of the specified tasks within existing resources and targets will allow to reduce the consumption of imported energy.

The traditional structure of the fuel balance of the metallurgical enterprises using natural gas as a substitute for coke in current conditions, Ukraine is ineffective because of the high cost of natural gas, which is close, and in some cases exceeded the cost of the replaced those quantities of coke. The task of streamlining the structure of the fuel balance by reducing natural gas consumption can be solved by replacing it with coke oven gas on previously developed by the Institute of ferrous metallurgy technologies. Instead used in blast furnaces, coke oven gas to cover the energy needs of other industries, primarily coke, the offered products of gasification not coking coals, and as units for gas blast furnaces, decommissioned according to a balance sheet metal.

The main problem in the use of blast furnace as a gas generator is that the temperature of the flue from the post of the charge gases exceeds the level permissible under the terms of the service life of the equipment load. To resolve this issue, you must use non-traditional reception, which consists in the fact that in the course of gasification produce two-stage cooling of gases: 1) by loading coal mixture of solid «coolers»; 2) the sharp cooling of gas at the exit from the post of the charge by submitting above the level of the stock line materials cooled furnace gas. Expediency of the organization of the second stage it is specified in the particular conditions. As a solid «coolers» slags are used silicon manganese, ferromanganese, Converter slag, welding slag and other, not containing higher oxides that form CO_2 when restoring, and to make useful and metal-containing slag forming components (Fe, Mn, MnO, CaO, MgO). Diagram of the technology includes (Fig. 3.7):

- loading in blast furnace combined with coal “coolers”, number and heat capacity of which provide the decrease of the temperature of the exhaust from the mines to the gases to between 800 and 950 °C, and does not include low-reducing oxides, that are forming in the shaft CO_2 and H_2O;
- flow above the surface of the stock line, which is situated at the lower edge of the top, refrigerated gases providing after mixing with mine gas specified allowable equipment operational conditions temperature furnace gas;
- cooling of the furnace gas to the lowest possible temperature, its compressing and injection through tuyeres, located above the surface of the stock line materials (recycling);
- selection “coolers” with the greatest possible content of useful components (iron, manganese and other), which increases the energy and economic efficiency of the technology and makes it a multi-purpose.

Adjust the temperature of gas you can also by varying the values of temperature and humidity of air. When using blast furnace as the core, there is a possibility to use as a “coolers” gas not only moisture and gases, but also hard lump materials, loaded with coal. These materials contain fluxing supplements and other useful components derived melts (pig-iron and slag) as by-products of coal gasification. Suitable for these purposes use of metallurgical slags: converter, welding, FeMn, SiMn with extraction of useful components in the melt. In this way, besides energy, are solving economic and environmental problems of an enterprise and industry. The use of slag as a “coolers” gas is solved important technological challenge: because they do not contain low-reducing oxides, giving oxygen in the mine “indirect” by, the exhaust gas is not updated with the gaseous products of recovery (CO_2 and H_2O), which reduce its calorific value, and the absorption of heat in the direct reduction of oxides increases cooling properties of slag additives.

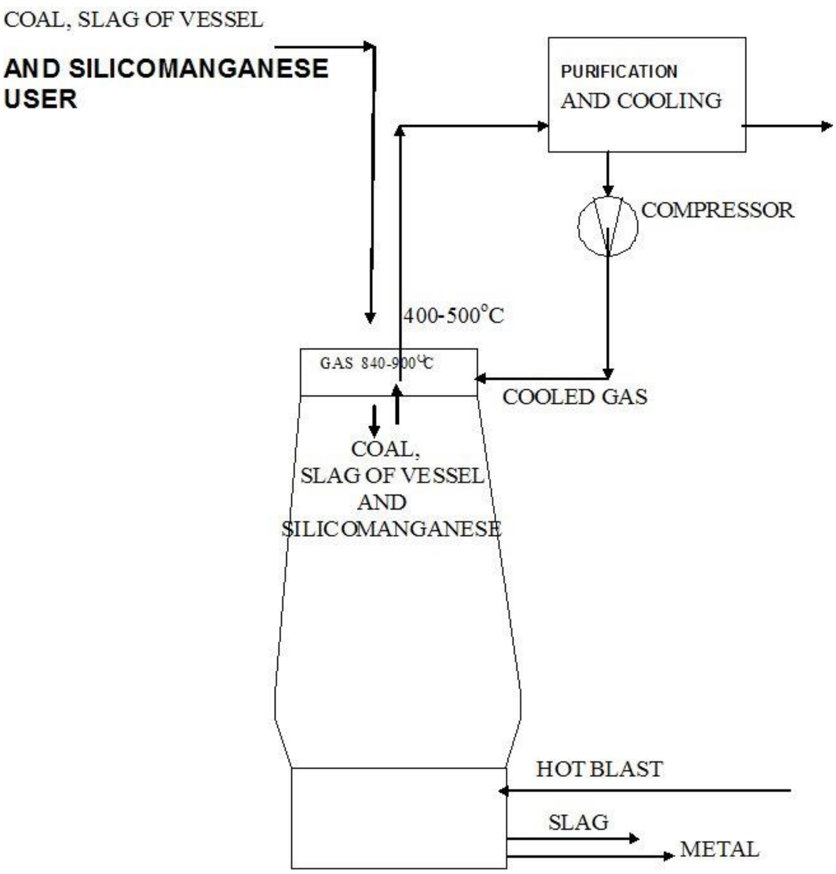

Figure 3.7. Schema of coal gasification in the blast furnace

Made on the basis of the methodology of calculation two-zone balance numerical analysis of the forecast showed the following characteristics:

- work with the hot blast requires additives pair to reduce the temperature of the tuyeres, as well as reduce the temperature of gas by adding solid «coolers» and the organization's top gas recycling; addition of steam and recycling unprofitable economically and in terms of fuel costs, additive solid «coolers» pays for itself at the expense of additional smelting of cast iron;
- work with nonheating ("cold") blast (about 200 degrees C) is possible without gas recirculation, but with the addition of solid «coolers» and a small enrichment of blast oxygen (22 to 25%), which in all variants are repaid additionally smelting cast iron.

Analytical study of the modes of operation of the unit according to the elaborated methodology showed:

- option considered blast, the most affordable and effective was the option of non-heating blast (200 degrees C) enriched with oxygen up to 23%;

- according to the criteria of the lowest fuel consumption and money costs on 1J gas priorities «coolers» arranged in ascending order of value, of silico-manganese slag welding slag - metal-containing fraction Converter slag - metal scrap, steel-making, but by the criteria of cash costs, given the cost of cast iron in the reverse direction;

- cost of conditional fuel per 1 MJ best gas fuel is anthracite, however, the monetary costs of using anthracite more than using lean coal due to the higher cost of the first; with the account of the given value of cast iron anthracite positive advantages, and the coke «walnut» - close to anthracite indicators;

- higher prices priorities regimes and resources are not changed.

When studying the temperature field and thermal operation of the height of the blast furnace-gas generator with the help of the developed mathematical model is S-shaped character of change of temperature of the charge and gas at the height of the furnace with more or less pronounced area of slow heat transfer.

The variants without gas recirculation location of the border between the upper and lower thermal zones, where are aligned flows of heat capacity of the charge and gases and the changing nature of heat exchange between them is in the interval of temperatures 870-910 °C, and is determined depending on charge the beginning of the reactions of decomposition of limestone, direct reduction and recovery of carbon dioxide. In variants with recirculation gas temperature of gas more than the variants without recirculation, which is achieved by lower consumption «coolers». Reduced ratio of heat capacities of the flow of the charge and the gases that leads to the displacement of the point of crossing of the thermal capacities burden and gas streams in the area with higher temperature 900-1000 °C.

The most cost-effective was the mode with “cold” blast (200 degrees C), enriched with oxygen up to 23% when loading metal-containing fraction Converter slag and mixture of anthracite with lean coal. The expected effectiveness of the implementation of the proposed regime of the new technology for blast furnace gas generator is useful volume 1719 m^3 includes two components:

- savings due to the replacement of the natural gas products of gasification of coal in the fuel units, or in a blast furnace 172,5 million UAH./year;

- cost reduction of pig iron produced from the coal gasification compared to the price of pig iron in blast furnaces that the coke - 224,5 million UAH./year.

One of the associated functions of blast-furnace is solid waste management, conversion in the blast furnace are deeper than in other aggregates: oxides are translated into metal and slag, and carbon - and carbohydrate components in the gas, and the gas filtration through the charge column can be managed from the position of absorption of a number of components, including hazardous substances. The efficiency of utilization depends critically on the preparation of waste. Iron - and carbon-containing wastes of metallurgy easily utilized by additives in the burden of sinter that it is possible and for waste from other industries, and domestic wastes corresponding to their education. Some of the waste may disposed of by filing in a ground state, together with the pulverized coal fuel, as well as injection at tuyere gasifies after the development of new technology. Nature dosage waste when filing the charge-depending on the preparation and content of various substances particularly harmful. It is unlikely, for example, possible to Orient the technology of smelting only on utilization of solid domestic waste, however, filing them in small doses into the blast furnace, working in the mode of coal gasification, is quite real when working out the method of preparation and study of the behavior of components in the conditions of the furnace.

Essentially passing, the function of utilization of technological and household waste may eventually acquire independent status as a function of the sanitary-ecological.

Thus, blast melting, as a multifunctional technology, can be focused on modes, which are dominated by one of the functions: metallurgical, energy and sanitary-ecological.

The first one includes production of metal and slag defined compositions and properties. In this function, blast-furnace smelting dominates the smelting of pig iron, the need of which in the foreseeable future will not diminish [57]. The evolution of technology of melt of pig-iron on the path of reducing the coke consumption up to 180-200 kg/t by blowing through tuyeres of large quantities of not coking coals and products of their gasification with subsequent transition to smelting without coke by complete replacement of coke coal. During this evolution is largely suppressed energy and limited to sanitary and ecological functions of metal-producing units in reducing the number of individual capacities in connection with the increase of their productivity. In these conditions, naturally using the unique properties of the blast furnace for increasing the effectiveness of all metallurgical complex is the optimization of energy and sanitary-ecological functions by transferring them to the individual (including backordered) units. As natural is the wide development of technology ferroalloys smelting in blast furnaces. Currently under intensive technology of smelting iron about half of the blast furnaces of Russia and Ukraine can be released to perform the functions ensure a sharp increase in energy and environmental efficiency of the entire metallurgical complex.

This concept of development of metallurgy is responsible evolutionary nature of progress in the industry, covering the deep socio-economic strata of the social organism. Now she acquires real features and is the basis for metallurgy of the XXI century.

Thus, the blast furnace smelting is a multi-functional system used for smelting of cast iron while obtaining a slag and other by-products and energy carriers. The specific properties of the system, that ensure its effective functioning in the dynamic industrial environment, are: a counter-current principle of continuous transmission of energy in a closed space; co-existence in the working volume of the materials in three States - solid, liquid and softened; the presence of a two-stage scheme of heat transfer at the height of the charge and the similar properties of the processes of mass transfer, forming the stability of processes in time and space. The pattern of processes periodic spontaneous shift melting modes in a different area are conditioned uncontrolled heterogeneity of the input parameters and the need to monitor the drift of parameters.

On the basis of a systematic analysis of the processes of blast-furnace identified and formulated the principles that determine the efficiency of measures on improvement of technologies**: 1. The principle of damping. 2. The principle of combination. 3. The principle of limiting conditions.**

The first and second reflect properties of the individual components of the system, the third - the General properties of a large system “Blast smelting”.

The blast melting, as a multifunctional technology, can be focused on modes, which are dominated by one of the functions: metallurgical, energy and sanitary-ecological. The first one includes production of metal and slag, which is dominated by the smelting of pig iron, the need for which will not diminish, and the evolution of technology on the path of reducing the coke consumption with subsequent transition to blast smelting without coke by complete replacement of coke by products of gasification of coals. During this evolution is suppressed the energy functions and limited to sanitary and ecological functions the number of metal-production units is reducing. In these conditions, naturally using the unique properties of the blast furnace is autonomization of energy and sanitary-ecological functions by transferring them (including backordered) at energy-ecological units, as well as the widespread development of technology of ferroalloys smelting in blast furnaces. Currently under intensive technology of smelting iron significant part of blast furnaces of Russia and Ukraine can be released to perform the functions ensure a sharp increase in energy and environmental efficiency of the entire metallurgical complex.

4. NORMATIVE ESTIMATION OF PARAMETERS OF THE BLAST-FURNACE SMELTING

The regulatory impact assessment of the parameters of the blast furnace to the coke consumption and blast furnace productivity refers to the definition of magnitude of change in coke consumption and performance when modifying the individual parameters of melting and their combination. The presence of such assessment, it is necessary to perform operational analysis of the technology, the performance of which depends on the completeness and quality of information used.

For the first time the technique of factor analysis was developed in the late 80-ies of the last century. After a series of discussions in enterprises and institutions of the sector, methods were considered at all-Union meetings of blast furnace, and then was approved as an industry policy paper in 1987 [61-64]. Further, the document specified in individual items in the metallurgical enterprises on the basis of practical data, analytical and experimental studies [65-71].

4.1 Methodical bases of formation of "simple" dependencies in a large system "blast melting"

During the study of the impact of individual factors on the indices of blast-furnace revealed its dependence on a set of associated conditions. Therefore, the evaluation of this impact cannot always because and largely depends on the task.

In the case of an isolated assessment of a particular factor should consider the whole complex of associated conditions.

When comparing the various periods of work to-day furnaces, when the separate components of this factor is already accounted for other factors, the value of its influence is limited to essential ingredient in order to avoid of “double counting”.

Operational analysis of changes in indicators of melting often use summary normalized coefficients counting coke consumption and productivity of the furnace, drawn up according to different data. The disadvantage of such briefs is not-interrelatedness of factors leading to errors in their absolute values and re-accounting of individual components effects in terms of the various factors.

For correct accounting of factors when analyzing the indices of blast-furnace needs to be taken to use special techniques, which are an integral part of metal-using the technique, the rationale and contents of which are summarized below.

The methodology is intended for use when analyzing the changes of specific consumption of coke and blast-furnace productivity caused by changes of the technological parameters of blast-furnace smelting. Such analysis is performed in comparison provision of periods of work of blast furnaces with different values of technological parameters of blast-furnace smelting, determining the value of a specific consumption of coke and performance (factor analysis). The basis of this analysis, lie the quantitative ratio between changed parameters (factors) and specific consumption of coke by productivity of blast furnaces), which define are empirically or analytically.

To get reliable results on the basis of empirical material need to connect it to a single logically consistent basis. Such a basis are the results of the analytical study of the process that acquire real content in contact with empirical material.

On the basis of established relationships completed an analysis of available experimental data, obtained in different conditions, and selected the most reliable of them. Summarized by these practices used for the adjustment of the figures derived analytically.

The results of the analysis with references to primary sources are given in the author's monograph "Cognition of processes and development of blast furnace technology" [68] and in Table 4.1 gives a summary of technological factors and the magnitude of their influence on the specific consumption of coke and the productivity of blast furnaces, established in the manner outlined, as well as references to the main sources containing the most characteristic results of the actual influence of technological factors on the specific coke consumption and productivity of blast furnaces.

4.2 An overview of the factors

In table 4.1 provides a summary of the technological factors and magnitude of their impact of the specific consumption of coke and productivity of blast furnaces installed given way, and links to primary sources, containing the most characteristic result of the actual influence of technological factors on the specific coke consumption and productivity of blast furnaces. When using data tables for mapping of periods of work of blast furnaces with different parameters and analysis of factors a specific consumption of coke and performance assume linearity and the autonomy of the influence of the each factor. In reality, the influence of the factors on the specific coke consumption and performance is non-linear and non-additively.

Table 4.1. Influence of technological factors on the specific consumption of coke and productivity of the blast furnace

№	Factors and units	+ increase, - decrease	
		Consumption coke, %	productivity, %
1	Elevated levels of iron in each 1 % (in all of the mixture without coke and CO_2 flux)		
	within up to 50 %	-1,4	+2,4
	Within 50-55 %	-1,2	+2,0
	Within 55-60 %	-1,0	+1,7
	The same, reducing the amount of slag on every 10 kg/t of cast iron	-0,35	+0,6
2	Increased consumption of pure metal-additives (100 % Fe) for every 10 kg/t of cast iron	-0,4	+0,6

3	Reducing consumption of raw limestone for every 10 kg/t of cast iron The same, dolomitized	-0,5 -0,4	+0,5 +0,4
4	Reduction of the content of the fraction 5-0 mm in the iron containing charge on each 1 %	-0,5	+1,0
5	Reduction of ash content in coke for every 1 %	-1,3	+1,3
6	Reduction of the sulfur content in the coke for every 0.1 % of [S] = 0,05 %	-0,18	+0,18
	When [S] = 0,04 %	-0,22	+0,22
	When [S] = 0,03 %	-0,27	+0,27
	When [S] = 0,02 %	-0,38	+0,38
	when [S] = 0,01 %	-0,71	+0,71
7	Increase of durability of coke: 7.1. by the indicator M_{25} (%/%): 7.2. by the indicator CSR (%/%):	 -0,6 -0,7	 +0,6 +0,7
8	Reduction of coke abrasion on the indicator M_{10} for every 1 %	-2,8	+2,8
9	Reduction in the content of coke: fraction +80 mm (for each 1 %); fraction – 25mm (for each 1 %)	 -0,2 -1,0	 +0,2 +1,0
10	Substitution of coke by lump anthracite, kg/kg	0,8 – 1,0	
11	Reduction in the content of silicon in the iron per 0.1 %	-1,2	+1,2
12	Reduction in the content of manganese in the iron per 0.1 % when 30 % of Mn ore output when 20 % of Mn ore output when 15 % of Mn ore output	 кg/t -1,17 -1,76 -2,27	 % +0,22 +0,35 +0,44
13	Reduction of phosphorus content in cast iron per 0.1 %	-0,6	+0,6
14	Increased sulfur content in iron:		
	14.1. In case of the arrival of sulfur 10 kg/t:	(kg/t:)	%
	0,04 - 0,05 %	-3,3	+0,6
	0,03 - 0,04 %	-5,5	+1,1
	0,02 - 0,03 %	-11	+2,0
	0,01 - 0,02 %	-33	+6,5
	14.2. In case of the arrival of sulfur 4 kg/t:		
	0,04 - 0,05 %	-1,3	+0,25
	0,03 - 0,04 %	-2,2	+0,4
	0,02 - 0,03 %	-4,4	+0,8
	0,01 - 0,02 %	-13,3	+2,5
15	Increasing the temperature of the blast each 10 °C in the ranges:		
	800-900 °C	-0,50	+0,50
	900-1000 °C	-0,40	+0,40
	a) when the concentration of oxygen in the blast up to 25 %		

	1000-1100 °C	-0,30	+0,30
	1100-1200 °C	-0,28	+0,28
	1200-1300 °C	-0,25	+0,25
	1300-1400 °C	-0,22	+0,22
	b) when the concentration of oxygen in the blast 25 – 35 %		
	1000-1100 °C	-0,25	+0,25
	1100-1200 °C	-0,20	+0,20
	1200-1300 °C	-0,20	+0,20
	1300-1400 °C	-0,18	+0,18
	c) when the concentration of oxygen in the blast 35 – 40 %		
	1000-1100 °C	-0,20	+0,20
	1100-1200 °C	-0,18	+0,18
	1200-1300 °C	-0,16	+0,16
	1300-1400 °C	-0,14	+0,14
16	A decrease in humidity blast on each 1 g/m^3 at a rate of blast:		
	1500-1600 м^3/t	-0,20	+0,14
	1000-1100 м^3/t	-0,15	+0,06
17	Enrichment of blast oxygen for every 1 % (abs.) in focus:		
	Up to 25 %	+0,50	+2,0
	25-30 %	+0,80	+1,7
	30-35 %	+1,10	+1,4
	35-40 %	+1,40	+1,6
18	Factor replacement of coke by coke oven gas at a flow rate:		
	Up to 200 м^3/t	0,45 кg/м^3	
	200-300 м^3/t	0,40 кg/м^3	
19	Factor replacement of coke by natural gas at a flow rate:		
	Up to 100 м^3/t	0,80 кg/м^3	-
	100-150 м^3/t	0,60 кg/м^3	-
	150-200 м^3/t	0,40 кg/м^3	-
20	Factor replacement of coke by fuel oil	1,2 кg/кg	-
21	Factor replacement crushed coke by coals:		
	anthracite and skinny with ash content up to 10 %	0,9 кг/кг	-
	the same, with an ash content of 10-20 %	0,8 кг/кг	-
	gas, with an ash content of 10-20 %	0,8 кг/кг	-
22	The increased pressure of top gases for every 10 kPa in the range up to 200 kPa (excess) with a corresponding increase in the mass of the blast	-0,20	+1,0
23	Decrease short-downtimes by 1 %	-0,50	+1,5
24	Reduction of time of slow run at 1 %	-0,50	+1,0

25	The reduction of cases of delays the release of pig-iron for every 1%, with the average duration of the delay of 0.5 interval of time between adjacent releases	-0,05	+0,1
26	The increase the forcing on the blast-melting process by an increase in the differential pressure gases for every 1 % up to the boundary values	-	+0,50
	The same, but above the boundary values	+0,2	+0,30
27	Increased uniformity of distribution of ore loads on the radius of the furnace top for conical charging devices Same for bell-less charging devices Replacement a conical by bell-less charging device	-(0-2,0)% -(0-3,0)% -4%	+(0-2,0)% +(0-3,0)% +4%
28	Reduction of heat removal from the walls of the furnace by 1% relative to the total ward heat, %	-100/dq , where: dq- the proportion of useful heat, %	-100/dq , where: dq- the proportion of useful heat, %

His character determined the General principles of interrelation of parameters of blast-melting set out in the article of Tovarovskiy I. G. The Philosophy of the Blast Smelting: Cognition and development of the technology [71], on the basis of which the estimation of the influence of each parameter on the consumption of coke and performance shall be based on the absolute value of the value parameter (the higher it is, the less the amount of influence), in combination with other parameters (some may reinforce other-other - weakening effect), the General level of perfection of the process (the higher it is, the less the effect of all parameters). The overall level of process perfection (the higher it is, the less the effect of all parameters). This complex of general laws of melting processes is expressed in the form of three principles of functioning and properties of a large system of Blast Furnace Melting:

Principles are: the attenuation, a combination, limiting states.

The properties: adaptivity, spontaneous shifts, multi continuity.

Therefore, the ranges of real values of some parameters of a break on the intervals within which without a considerable error of communication can be considered linear, and the value the influence of some factors on the consumption of coke and performance of furnaces are given depending on the average level of other factors.

Shown in the table 4.1 factors are grouped into three categories: charge (items 1-13), gas-blowing (items14-20, 25) and organizational (items 22-24). Following are the features of formation and accounting of each category of factors.

The most significant changes and clarifications the following new methods:

1. Added a new position on Coke: "7.2. indicator CSR" and "10. Substitution of coke with lump anthracite" and the position "23. The increase in the degree of melting force...".

2. Clarification and differentiation effect recovery of manganese in cast iron and sulfur transfer to the slag, depending on the quantity of these components in the mixture (items 6, 12, 14).

3. Clarification in the direction of decreasing the coefficient of replacement of coke by natural gas at the rate greater than 100 m^3 /t (item 19) that is associated with the established in the course of the research the specific change of the temperature field of a heat charge materials in case of reduction degree of direct reduced below 20%.

4. Based on studies and mathematical modeling of processes in a blast furnace, burden materials distribution on a 10-point equal area annular zones of the cross section of the furnace top for the first time given the forecast assessment of the influence of character of distribution of material and gas on the basic parameters of melting in a quantitative form (item 27). In the first stage assessment is not included in the total adjustment of coke consumption, and is used in the comparative analysis. For inclusion will be developed differential scale distribution of ore loads on the radius of blast furnace.

5. The possibility of estimation of influence of thermal losses on the coke consumption and productivity (item 28).

4.3 Charging options

Since the content of iron in agglomerate depends on basicity, should operate the generalized index - iron concentration of conditionally self-fluxed charge. It is defined as the amount of iron in all components (including limestone, metal-additives, slag additives etc.), in addition to coke, divided by the total consumption course of these components without CO_2 carbonates. Thus, consumption of raw flux is the sum of the components of the charge less contained CO_2.

The specified index of the content of iron, you can compare the wealth blends with different basicity and exclude having a place ambiguity of the current rate of maintenance of iron in agglomerate. Iron content in semi-самоплавкой charge is surely connected with the release of slag on 1 t pig-iron. Therefore, the analysis can be operated on only one of these values.

Increased content of iron for every 1 % at the same oxidation corresponds to the decrease in the number of slag value: $\Delta Ш=100Fe_ч/(\% \ Fe)^2$, kg/thm.

Where: $Fe_ч$ - the amount of iron in iron, kg/t of pig iron; % Fe - average content of Fe in self-fluxing charge, %.

When $Fe_ч$ = 940 kg/t and % Fe = 50 % value $\Delta Ш$ = 37,6 kg/t.

When $Fe_ч$ = 940 kg/t and % Fe = 55 % value $\Delta Ш$ = 31,0 kg/t.

When $Fe_ч$ = 940 kg/t and % Fe = 60 % value $\Delta Ш$ = 26,0 kg/t.

With the average content of iron in agglomerate 50 % of changing it to 1 % leads to a change in the amount of slag 1.4 times greater than in the case of the average iron content of 60 %. For this reason, saving coke and increase productivity on the every additional 1 % of iron in agglomerate obtained in conditions of Ukraine, 1.4 times higher than in Russia. Largely for this reason, the efficiency of increase iron content through the input to the charge of pellets in some cases lower than in the case of increasing the content of iron in agglomerate there. A decrease of the slag for every 10 kg/t of pig iron contributes to the economy of coke 0,35 % and a rise of productivity of 0.6 % regardless of its total amount and content of iron in the charge.

Consumption of metal-additives affects the consumption of coke through the content of iron in agglomerate (number of slag) (item 1) and heat consumption and carbon on the direct reduction, changing under the influence of change of a degree of metallization, which is determined as the ratio of the number of metallic iron in the charge to the entire gland charge. Because the accounting for the maintenance of iron in agglomerate is provided in a separate item (item 1), the flow of net of metal-additives (item 2) takes into account only the change in metallization of charge. If necessary, isolated assessment of the impact of metal-additives when changing the number of slag is not accounted for separately, it should be taken into account (3-5 kg/t of pig iron slag for every 10 kg/t of pig iron metal-additives) in General value of efficiency. Then saving coke from higher consumption of pure metal-additives (100 % Fe) for every 10 kg/t of pig iron at 0.6 %, and the increase of the production capacity of 0.8 %. For contaminated metal-additives efficiency is proportional to Fe (kg/kg).

The degree of fluxing the charge affects the consumption of coke and performance through the contents of iron and consumption of raw flux. The first factor is taken into account when counting those changes in the content of iron in the conditionally self-fluxing charge, the second should teach remain separately (item 3). Outlined the way of accounting for the characteristics of the charge eliminating the need to enter a dimension such as the share of sinter and pellets, as the latter affects the consumption of coke output slag (iron content), flux consumption (item 3) and coal content in the charge (item 4).

Material characteristics coke (items 5, 6) and the composition of iron (items 10-13) affect the consumption of coke as directly through the heat balance and balance of carbon and through changes in the amount of slag and raw flux. Since the total change in the quantity of slag (Fe content) and crude flux is accounted for separately (items 1, 3), the value of the influence factors on the consumption of coke and performance under items 5, 6,10-13 include only the effect of direct influence of factors on the heat balance and the balance of carbon.

If you want to evaluate the influence of each of the factors considered in isolation, when the total change in the amount of slag and raw flux is not accounted for separately, you should consider this change in the overall magnitude of impact of each factor on the consumption of coke and performance (table. 4.2; the numerator in the absence in the charge of raw flux or constant consumption, denominator - if you change the quantity of CaO in charge change in the flow rate of raw flux).

Impact strength (item 7) and attrition (item 8) coke takes into account the have-growing mutual relationships between the indicators M_{25} and M_{10}. If necessary, the isolated bathroom assessment of the impact of each of these indicators should be assessed increase for every 1 % of the M_{25} savings of coke and increase the productivity of blast furnace 1.5 %, and the indicator M_{10} - values given in the table 4.1.

Table 4.2. Isolated assessment of the impact factors onthe specific consumption of coke and productivity of the blast furnace

Factors and units	+ increase, - decrease	
	coke consumption, %	Productivity, %
Reduction of ash content in the coke on 1 %	-1,4/-1,8	+1,4/+1,8
Reduction of the sulphur content in the coke		
for every 0.1 % of [S] = 0,05 %	-0,18/-0,57	+0,18/+0,57
[S] = 0,04 %	-0,22/-0,70	+0,22/+0,70
[S] = 0,03 %	-0,27/-0,92	+0,27/+0,92
[S] = 0,02 %	-0,38/-1,36	+0,38/+1,36
[S] = 0,01 %	-0,71/-2,66	+0,71/+2,66
Reduction in the content of silicon in the iron 0.1 %	-1,2/-1,0	+1,2/+1,0
Reduction of content of manganese in the iron	кg/thm	%
at 30 % Mn in the output Mn-ore	-1,17/-1,66	+0,22/+0,33
at 20 % Mn in the output Mn-ore	-1,76/-2,89	+0,35/+0,42
at 15 % Mn in the output Mn-ore	-2,27/-3,78	+0,44/+0,61
Increased sulfur content in iron:	кg/thm	%
in case of the arrival of sulphur with the charge 10 kg/t		
From 0.04 to 0.05 %	-3,3/-13,0	+0,6/+2,4
From 0.03 to 0.04 %	-5,5/-21,7	+1,1/+4,3
From 0.02 to 0.03 %	-11/-43,3	+2,0/+7,19
From 0.0 1 to 0.02 %	-33/-130,0	+6,5/+25,6
In case of the arrival of sulphur with the charge 4 kg/t		
From 0.04 to 0.05 %	-1,3/-5,1	+0,25/+0,99
From 0.03 to 0.04 %	-2,2/-8,7	+0,4/+1,58
From 0.02 to 0.03 %	-4,4/-17,4	+0,8/+3,15
From 0.01 to 0.02 %	-13,3/-52,4	+2,5/+9,85

4.4 Blast parameters

The impact of the blow parameters on the specific consumption of coke and productivity of the furnace is characteristic of high non-linearity and dependence on many conditions. For this reason, the conversion factors given ranges of parameter values, and in dependence depending on the values of other parameters.

To the greatest extent it refers to the blast temperature, consumption of natural gas and oxygen.

The effect of the concentration of oxygen in the blast on the consumption of coke is ambiguous and depends on the initial conditions. When working on a cold or low-heated atmospheric blast oxygen additive promotes economy of coke. In the conditions of high-heated blast with a high concentration of oxygen and low hydrocarbons additional enrichment of blast oxygen without the addition of hydrocarbons leads to excessive consumption of coke. The second of these modes is typical for most modern furnaces that use oxygen when heated blast up to 1000-1300 ^{o}C. Some over-expenditure of coke (item 16) takes place on these furnaces, despite the reduction of specific heat losses in enrichment of blast oxygen (without additives of natural gas) with fixed (and in some cases less) direct reduction.

The coefficients of replacement (KR) coke gaseous and liquid blast-additives depend on all the parameters that determine the character of the temperature field in the furnace (item 14-19). Generally the more, the higher the original importance of the acquisition of theoretical combustion temperature. For the value, this temperature 2,000 ^{o}C. KR coke by natural gas is 0,9-1,0 kg/m^3 at low consumption, falling to 0.7-0.3 kg/m^3 at a consumption 150-200 m^3/t. Similarly KR of coke by coke oven gas is 0.40-0.45 kg/m^3. KR of fuel oil is little dependent on the total flow rate and is 1.4 kg/kg. KR of crushed coal is mainly determined by its composition and equal for anthracite 1.0 kg/kg, and for gas coals and lean coals 0,8-0,9 kg/kg.

The values of KR of coke can be obtained in the case of complete transmutation of hydrocarbons, and solid carbon at the tuyeres. When existing ways of their input and distribution on tuyeres part of hydrocarbons subjected to pyrolysis with generation of soot and coal particles are burned incompletely. Given this, the practical value of KR coke adopted by 15-20 % below the limit for natural gas, fuel oil and coal (items 18, 19, 20). For coke oven gas specified effect is negligible (item 17). Increased intensity of melting at forced during the process leads to the increase of the share of coke consumption. The value of the over consumption of coke from the higher-intensity of melting the more than lower specific consumption of coke and less of his strength, more small fractions in the furnace and a higher concentration of oxygen in the blast, as well as smaller stay charge materials in the furnace.

In the case of increasing the intensity due to factors that reduce the consumption of coke, for example, fines trifles of charge, sharing an increase in consumption of sour-kind and natural gas and other expenditure coke explicitly not observed and decreases the total value of savings. In this case, the influence of the intensity of the melting not require separate accounting as a component of the total value of changes in consumption of coke from the effects of the main factor. Separate accounting of the impact of melting intensity required in case of changes of intensity of gas-dynamic regime, which are expressed in the change of the differential pressure of gases in the furnace (item 25). This is due to changes in the volume of gases per unit of time with irregular gas permeability post of the charge, and also due to changes o permeability post of the charge for the same amount of gases per unit of time. The increase in differential pressure and a corresponding increase in the intensity of blast-melting leads to increased productivity of the furnace. The increase in differential pressure and a corresponding increase in the intensity of blast-melting leads to increased productivity of the furnace. The excess of some boundary differential pressure leads to an increase in consumption of coke and a corresponding slowdown in the growth of productivity of the furnace. The boundary values of differential pressure (ΔP_b) for blast furnaces of different volumes are approximately:

1000-1242 m^3 - 130 kPa;
1300-1800 m^3 - 140 kPa;
2000-2300 m^3 - 150 kPa:
2700-3200 m^3 - 160 kPa;
5000 m^3 - 180 kPa

For the specific conditions they should be clarified by the expression:

$\Delta P_b = \Delta P_b^o \cdot 450/k$, where k - coke consumption, kg/t.

4.5 Fluctuations of the charge composition and parameters of technology

Shown in the table 4.3 data are intended for isolated evaluation of each the Treaty of factors, when the total change in the quantity of slag, silicon content in the iron and differential pressure of gases in the post of the charge is not accounted for separately. When evaluating the influence of the complex of parameters (tab.4.3), where the impact of the changes in the number of slag (maintenance of iron in agglomerate), silicon content in the iron and differential pressure in the furnace is recorded gross (regardless of the determining factors), separate accounting for the effects of variability charge composition and parameters of the heat is not required.

Table 4.3. The impact of fluctuations in the parameters on the consumption of coke and productivity of the furnace

Reduction of RMS deviation factors	Savings coke, %	Performance Increase, %
Error dosing of charge 0.1 %	0,28	0,42
Coke humidity 0.1 %	0,28	0,42
Ash coke 0.1 %	0,36	0,54
Maintenance of iron in agglomerate by 0.1 %	0,20	0,29
Basicity of charge 0.01	0,13-0,19	0,22-0,33*
The temperature of the blast 10°	0,08	0,13
Humidity blast 0.1 %	0,45	0,67
Natural gas consumption for 1 m3/t	0,42	0,63
The concentration of oxygen in the blast 0.1 %	-	0,22

* Smaller values when exiting slag 300-350 kg/t of pig iron, large - at 450-500 kg/t of cast iron.

4.6 Organizational factors and General comments

The institutional factors technologies relate stop and quiet running up-term furnaces, rhythm charging and tapping, as well as associated with these factors stability of the process. The influence of these factors on the specific coke consumption and productivity of the furnace depends on the nature of transients caused by them, and therefore not always explicitly. Until this influence is assessed empirically, based mainly on the statistical production data (items 22-24).

Impact of most of the factors discussed above sufficiently studied and largely amenable to quantitative analysis within a single logical scheme of blast-furnace smelting. The influence of some of them, studied not enough is considered in isolation, on the basis of generalization of experimental data. These include mechanical and physical-chemical properties of raw materials and coke, natural gas distribution in the furnace, the characteristics and dynamics of changes of elements of the profile of the furnace (and therefore heat loss), processes in the forge migration alkalis and carbon.

These factors with direct impact on the specific consumption of coke and productivity of the furnace are in close relation with other parameters of melting and may modify the nature of the influence of these parameters on the indicators of the processes. For reliable their assessment requires further study and mathematical description of processes. At this stage uses only some empirical data (items 4, 7, 8, 22-24).

4.7. Normative document

Based on the study and mathematical modeling of the processes of blast furnace melting, as well as the generalization of the operating experience of the furnace furnaces, general principles for their functioning have been established and a normative assessment of the effect of process parameters on coke consumption and blast furnace capacity is given. This normative assessment is the methodological basis for performing an operative analysis of technology and the content base of the guiding technological document used at enterprises since 1987.

The new document was substantially supplemented and refined based on the results of the analytical and experimental studies carried out in the past years, as well as the generalization of the experience of the operation of blast furnaces. This version for the first time has an effect on the coke consumption of the nature of charge material distribution during loading.

5. CONCLUSION

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 stability in a dynamic industry environment: by the end of each century the specific productivity of the best blast furnaces increased exponentially and seeks to 12-15 thousand t/m^3.d, the coke rate lowered linearly and seeks to 200-250 kg/thm.

Analysis of blast furnace smelting assumes a solution of two base tasks: study of interrelations of parameters and characteristics of real blast - furnace smelting; forecasts of expected characteristics of blast - furnace smelting on preset parameters of work. 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 blast furnace height: material distribution in the furnace based on the parameters of charging; multi-zone model of heat-and mass transfer; physico-chemical transformations and mechanics of material and gases.

Developed in Iron and Steel Institute National Academy of Science of Ukraine mathematical model of blast-furnace processes is builded 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.

Analytical studies performed with the use of a multi-zone mathematical model 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 intersecting 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 parameters on coke consumption and other smelting indices in particular:

1. An increase of the consumption of natural gas (NG) decreases direct reduction and lowers the rate of heat transfer in the lower region of the furnace while increasing it in the upper region. This increases the losses through the top and causes the softening and melting zones (SMZ) to rise above their base position and expand. The differential coke-replacement coefficient (DCR) 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 then reduced more rapidly, decreasing by a factor of 1.5-4 at NG > 100 m^3/ton, when the degree of direct reduction decreases to r_d < 20%. The same effect is obtained when coke oven gas (COG) is injected and COG = 2 NG.

2. 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 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 NG and becomes of little significance at NG > 100 m^3/t. Calculations have shown a slight change to the extent of direct reduction and specific heat losses by increasing the oxygen concentration. As a result of this decisive influence on the heat balance provides an exception from the blast parts nitrogen and corresponding reduction in the parish of heat in the process. The results of the calculation differ some from earlier adopted: the increase in consumption of coke for each additional 1% oxygen in the blast 0,5 - 1,45% vs. 0.1%to 0.5%; 2) the performance increase of 0.9 - 2.7 %a/% against 1,0 - 3,0 %/%.

3. With an increase in blast temperature Tb in the high-temperature zones (900°C), more mass of gas passes through the more permeable radial annular zones (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 more permeable 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. 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. 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 Tb; 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°).

4. With an increase in the consumption of pulverized-coal fuel (PCF), the temperature field of the furnace changes under the influence of the same tendencies that are seen with the injection of NG and COG. However, the changes are smaller and are not the same for different conditions. 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 (Ap = 10%, Cp = 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.

5. Lack of resources, low-ash coal for pulverized coal injection – PCI (pulverized coal fuel - PCF) requires solutions to technical problems of the use of high-ash coals, in particular, partial and full gasification of fuel before entering the tuyere area of BF.

Injection of the products of coal gasification (PCG) instead of PCI into the blast furnace tuyeres eliminates these limitations.

It was studied the influence not only of individual parameters, but also the complex of factors on consumption of coke. 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 ArselorMittal Krivoy Rog (henceforth referred to as AMKR) and 5500-m^3 BF-5 at the Severstal plant. 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 COG 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 found that use of the offered modes will allow to cut expenses coke to 180-200 kg/t of pig-iron.

Use of effective technology of pulverized coal injection should be accompanied by the development of additional and alternative technologies. In particular, consideration should be given to technologies that combine PCF injection with the injection of coke-oven gas, products from the gasification of widely used low-grade coals, and other fuel additives, as well as the charging of specially prepared lump anthracite. Because the amount of coal which can be injected could be increased significantly by subjecting it to preliminary gasification and fluidizing the ash in tuyere-mounted gasifiers means that the targeted savings of coke could be realized by replacing coke with either high-grade coals (in the form of PCF) on low-grade coals (in the form of CGPs). In this case, for the best variants of the technology the ratio of the equivalents for the replacement of coke by coal is close to the ratio of the contents of carbon in the low- and high-grade coals (0.65 in the present case 0.65).

The blast-melting as phenomenon deserves special consideration in terms of its specific and system properties, providing stability in a dynamic industry environment. The properties are:

- 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 of 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.

- Two-stages scheme of heat exchange gives a flexibility smelting technology to changing the modes and provides stability to the process to external influences due to the presence of a “reserve zones”, which soften the heat rejection.

- The specified property is inherent in the processes of restoration of oxides, packed bed of coke, changing the state of materials and other.

- Influence of the chemical composition of slag on its properties (crystallization temperature, viscosity and other) and stability of the properties (stability slag).

- Drift indicators melting during the same mode, that is conditioned by distribution of the environment and its properties in the volume of each aggregate and deforming over time average parameters and indicators of melting with the accumulation of new properties, enabling spontaneous shift the status of the processes in a different area and require adjustments to the regime to achieve the targets.

From the middle of the 19th 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». In the field of blast furnace processes mathematical modeling takes a big place. Developed in Iron and Steel Institute National Academy of Science of Ukraine mathematical model of blast-furnace processes is builded on the basis of the structural linkage of multiband height and the radius of the blast furnace and General balance of mass and heat.

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 direct reduction and other. The study of the influence of the input parameters of the heat on the formation of the temperature-concentration phase fields showed significant quantitative differences for different settings. It was revealed and clarified some of the regular dependences of heat exchange processes and phase transformations in materials, some of which qualitatively confirmed previously conducted experimental studies and can be used to improve technology and further the study of the processes of blast-furnace.

On the basis of a systematic analysis of the processes of blast-furnace identified and formulated the principles that determine the efficiency of measures on improvement of technologies:

1. The principle of damping: MAXIMUM EFFECT FROM APPLICATION OF EACH MEASURE ON IMPROVEMENT OF BLAST-FURNACE SMELTING IS ACHIEVED UNDER CONDITIONS, THAT OPPOSITE THOSE, TO WHICH LEAD THESE CONDITIONS.

2. The principle of combination: THE MOST EFFECTIVE COMBINATION OF SUCH MEASURES, WHICH AFFECT THE BASIC PROCESSES IN THE FURNACE IN OPPOSITE DIRECTIONS.

3. The principle of limiting conditions: AS TECHNOLOGY IMPROVED, BLAST-FURNACE SMELTING AND PROXIMITY TO SOME LIMIT REGIME EFFICIENCY OF THE ENTIRE SET OF ACTIVITIES FOR FURTHER IMPROVEMENT OF REDUCED.

The first and second reflect properties of the individual components of the system, the third - the General properties of a large system “Blast smelting”.

The evolution of the blast furnace smelting is going on the path of reducing the coke consumption as energy savings, and by substitution of coke less scarce fuel. Development of technology of pulverized coal injection (PCI) with submission in the blast furnace up to 250 kg/tm PCI of low-ash coal and technology injection of an equivalent amount of gasification products of high-ash coals with the General improvement of the technological mode and quality of charge allow to hope for achievement of coke consumption 180 - 200 kg/tm. Further evolution of the blast furnace, related to the restructuring of the technology and design for the purpose of transition to obtaining metal without coke. The regularity of this course of development are conditioned to the specific properties of the blast furnace smelting as a large system and further developments of the works, that was begin by D. K Chernov.

The results of developments showed that the major advantage of the technology without coke (TWC) in shaft-hearth unit (SHU) is less cost of fuel and is missing emissions from coke production. Further, the structure of the metal may be adjustable from cast iron (4,5%), to steel (1,5-2%).

As a product of natural evolution of the blast furnace smelting the technology without coke in the SHU (with the cost of fuel on 21-23 % less than in the BF, and 6-8 % less than in COREX) can be organized at the existing enterprises in the framework of reconstruction of blast furnace with the term of payback of less than 1 year. This approach to industrial restructuring without conflict solves the main socio-structural problems of the industry and the enterprises which is not less significant positive factor than all the rest.

The blast melting, as a multifunctional technology, can be focused on modes, which are dominated by one of the functions: metallurgical, energy and sanitary-ecological. The first one includes production of metal and slag, which is dominated by the smelting of pig iron, the need for which will not diminish, and the evolution of technology on the path of reducing the coke consumption with subsequent transition to blast smelting without coke by complete replacement of coke by products of gasification of coals. During this evolution is suppressed the energy functions and limited to sanitary and ecological functions the number of metal-production units is reducing. In these conditions, naturally using the unique properties of the blast furnace is autonomization of energy and sanitary-ecological functions by transferring them (including backordered) at energy-ecological units, as well as the widespread development of technology of ferroalloys smelting in blast furnaces.

When increase the development of the main functions of the blast furnace (ironmaking) the role of additional weaken and become available capacity, which can be used for other purposes. So, redundant blast-furnace can be used for gasification of coals. When using blast furnace as a gas-generator (BF-GG), there is a possibility to use as a “coolers” gas not only moisture and gases, but also hard lump materials, that was loaded with coal. These materials contain fluxing supplements and other useful components derived melts (pig-iron and slag) as by-products of coal gasification. Suitable for these purposes use of metallurgical slags: converter, welding, FeMn, SiMn with extraction of useful components in the melt. The use of slag as a “coolers” gas is solved important technological challenge: because they do not contain low-reducing oxides, giving oxygen in the mine “indirect” by, the exhaust gas is not updated with the gaseous products of recovery (CO_2 and H_2O), which reduce its calorific value, and the absorption of heat in the direct reduction of oxides increases cooling properties of slag additives.

Numerical analysis showed that work with non-warming (“cold”) blast (about 200 degrees C) is possible without gas recirculation, but with the addition of solid «coolers» and a small enrichment of blast oxygen (22 to 25%), which in all variants are repaid additionally smelting cast iron.

Analytical study of the modes of operation of the BF-GG showed:

- option considered blast, the most affordable and effective was the option of non-warming blast (200 degrees C) enriched with oxygen up to 23%;

- according to the criteria of the lowest fuel consumption and money costs on 1J gas priorities «coolers» arranged in ascending order of value, of silico-manganese slag welding slag - metal-containing fraction Converter slag - metal scrap, steel-making, but by the criteria of cash costs, given the cost of cast iron in the reverse direction;

- cost of conditional fuel per 1 MJ best gas fuel is anthracite, however, the monetary costs of using anthracite more than using lean coal due to the higher cost of the first; with the account of the given value of cast iron anthracite positive advantages, and the coke «walnut» - close to anthracite indicators;

- by higher prices priorities regimes and resources are not changed.

The results of study the temperature field and thermal operation of the height of the BF-GG: the isotherms have S-shaped character of change of temperature of the charge and gas at the height of the furnace with more or less pronounced area of slow heat transfer.

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doctor of technical sciences, professor, academician of the Academy of Mining Sciences of Ukraine, laureate of the NAS of Ukraine award, author of 500 scientific works, including 22 monographs, 10 brochures and 70 inventions.

SCIENTIFIC ACTIVITY.

1. Analytical and experimental studies of blast furnace smelting using mathematical modeling. System analysis of blast melting.

2. Coke-Saving in Blast Furnace. Non-traditional metallurgical technologies based on the use of gasification products of low-grade coals. Low-carbon and non-coke-blast furnace melting.

3. Optimization of Blast Melting modes. Theoretical and technical solutions of low-coke and non-coke Blast Melting by injection of coal gasification products. Use of blast furnaces for gasification of coal with utilization of waste

INDUSTRIAL REALIZATION OF SCIENTIFIC DEVELOPMENTS

1. A set of decisions on blowing parameters of the Blast furnaces of Ukraine - 1980-1995.

2. Technology of blast furnace smelting with injection of coke oven gas through tuyeres to replace natural and coke saving (Makeevsky MC - 1980-1992).

3. Annual (1967-1995) analytical and summarizing developments for the blast furnaces of the industry, used to improve the technology of DP.

4. Technology of blast-furnace smelting with the replacement of 10-15% of coke by lump anthracite in blast furnaces of the Krivorozhstal steelworks - 2000-2011.

5. Recommendation for blast-furnace production of coke-conserving and non-traditional low-carbon a technologies (2000-2015).

SOCIAL ACTIVITY

1. 2001 - 2008 - work as a part of the Expert Council of the Higher Attestation Commission of Ukraine.

2. Since 2001 - working in the section "Technical and technological problems of sustainable development and system monitoring of the environment" of the Scientific Council of the National Academy of Sciences of Ukraine.

3. Since 2006 - working in the metallurgy section of the Committee of State Prizes of Ukraine in the field of science and technology.

4. From 2013 - working in the editorial board of the magazine "Energy Science and Technology" (Canadian R & D Center of Sc & Cult) as deputy. Editor-in-chief.

5. Since 2016. Member of the editorial board of the journal "Bulletin of Information of metallurgy.

6. In 2018 three books editions of the author are submitted for consideration at the 38th Paris International Book Salon (LIVRE PARIS). 19.03.2018: The annotations of the books were included in the catalog of the International Paris Book Salon (March 16-19, 2018, Paris). Each of the three editions is awarded the "Golden" Salon Medal.

Among the 22 monographs published by the author in 50 years, the following are considered to be the most popular, among which there will be recognition and release of the English Minimonograf:

- Blast Furnace melting in powerful furnaces. Moscow, Metallurgia Publishers, 1968, 116 pages. Co-authors R.D. Kamenev G.B. Rabinovich ..
- The adoption of mathematical methods and computers for the analysis and management of the Blast melting process. Publishing house "Metallurgy", Moscow. 1978, 264 p. Co-authors EI Raikh, KK Shkodin, VA Ulakhovich,
- Perfection and optimization of the parameters of the Blast furnace process. Moscow. "Metallurgy". 1987, 192 p. Without co-authors.
- Evolution of blast furnace smelting (monograph). Dnepropetrovsk, publishing house "Thresholds", 2001, 424 p. Co-author V.P. Lyaluk.
- Blast furnace melting. 2 edition. Dnepropetrovsk, publishing house "Thresholds", 2009. 768 p. without co-authors.
- Cognition of the processes and the development of technology of blast-furnace melting 3 edition. Publishing House "Zhurfond", 2015, 912 pp. Without co – authors.
- Blast furnace smelting with injection of coal gasification products. Kiev, publishing house "Naukova Dumka", 221 p. Co-author Merkulov A. Ye.
- Cognition of the processes and the development of technology of blast furnace melting. Collective work of the 2nd International Symposium. Dnepr, Zhurfond, 2016, 383 p. Team of authors.

Minimonograph

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