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The Analysis of Coke-Saving Modes of Blast furnace Smelting on the Example of Blast Furnace No.9

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The analysis of coke-saving modes of blast furnace which was performed basing on the developed in the Institute of Ferrous Metallurgy NAS of Ukraine mathematical model, showed the possibility of a step-by-step implementation of alternative modes: the charge of lump coal into the furnace with improved properties of raw materials - the use of pulverized fuel - injection of coal gasification products. This scheme will reduce coke consumption to the level of 200 kg / t of pig iron.

Keywords: BLAST FURNACE SMELTING, COAL GASIFICATION PRODUCTS, PULVERIZED COAL, COKE

With the increase of metal production in limited volumes of coking coal resource base the problem of coke saving acquires paramount importance in the development of metallurgy. The solution of the problem is carried out in two ways: reduction of smelting heat demand due to the charge preparation and improving the organization of technology, substitution of coke with less expensive utility products. The effectiveness of the second way depends on the properties of the substituting utility product and its cost; and its implementation is always associated with the need to use the first direction.

In the blast furnace smelting coke serves as a complex energy technological material: along with power supply of the processes it is a solid checker in the area of softening and melting of iron-containing materials, providing countercurrent of burden and gases in the furnace, as well as a controller of gas distribution in the area of cross section of the unit. Because of the complexity of these functions the substitution of coke in blast furnace smelting with other fuel components can not be considered only from the point of thermochemical views; it requires a comprehensive analysis of all the technology in order to identify modes providing an effective solution to the problem, i.e. development of new technology [1].

In the conditions of market environment with a dynamic change in the prices for fuel it is required to have a wide arsenal of technologies of substitution of coke with different energy sources, allowing to implement the most effective option in each segment of time.

For the conditions of PJSC "ArcelorMittal Krivoy Rog" (PJSC "AMKR") a strong dependence of the efficiency of smelting in general and individual measures to reduce the consumption of coke on metallurgical characteristics of coke raw material is indicative [2, 3]. This is especially important when replacing a large amount of coke with pulverized coal (PC) and is a determining factor in deciding about the implementation of the pulverized coal injection technology. Since the issue of improving the metallurgical properties of raw materials and coke is a long-term task, its decision must anticipate the implementation of pulverized coal injection; and after the conversion of blast furnace smelting for high-quality iron ore and coke there will be obtained an effect, the significance of which is comparable with the effect of pulverized coal injection.

The calculations for the conditions of the BF-9 of PJSC "AMKR" [4] have shown that the implementation of a set of measures necessary for the effective implementation of pulverized coal would allow to reduce coke consumption to 378 kg/t, and at loading lof ump anthracite (70 kg/t, a mastered technology) coke consumption would be 318 kg/t. Thus, the next phase of development of the technology on this BF will be highly effective in replacing the part of the coke with lump anthracite, the use of which does not require significant capital expenditures.

The further development of the technology is connected with the injection of pulverized coal.

Table 1. Coal compositions, accepted for the calculation of the parameters of BF at the injection of PC and CGP

Coal for injection	Ash, %	Volat., %	S, %	H, kg/kg	N, kg/kg	O, kg/kg	H_2O, kg/kg	C_{vol}, kg/kg	C_{Σ}, kg/kg	C, kg/kg
PC	10	13	1.2	0.040	0.015	0.025	0.01	0.050	0.798	0.748
CGP	25	25	1.2	0.050	0.025	0.075	0.01	0.10	0.578	0.478

The implementation of expected results of pulverized coal injection requires solution of complex of problems of radical improvement of metallurgical properties of coke and iron ore [5, 6], as well as the development the methods of processes management at low coke consumption. The solutions to these problems are known, and the difficulties of implementing in limited scales can be overcome. However, at solving the problems at the level of the industry there are serious limitations due to, inter alia, lack of coking coal and coal for PC preparation [7].

These limitations, which were not noticed in the initial period of expansion of pulverized coal injection in Europe and Asia, now are indicative not only for Ukraine and Russia, but soon, with the exhaustion of resources, will cause conjunctural effect on the development of the world's steel industry. Considering the above, PC injection development should be combined with the development of alternative coke-substituting technologies combining injection of pulverized coal with natural, coke gas, etc. at loading of lump coke and coke nut into the BF.

Because of the increasing shortage of low-ash coals for PC preparation, a fundamental solution of the problem of reduction of coke consumption to 180-200 kg/t of pig iron using low-grade coal for its replacement can be obtained through the development of a new technology of blast furnace smelting with the injection of hot reducing gases – coal gasification products obtained in special gasifiers – tuyere (in BF) and blast-furnace (in some units) [1]. One can hope that the expected difficulties of the development that started in 1980-1982, and the complexities of its implementation will not be an obstacle to understanding the real situation with the resources of coal and explanation of the urgency of practical solution of the problem, the relevance of which was designated long time before [1].

The essence of technology with injection of PC is as follows. Each tuyere device of BF in the area "bootleg-nozzle" is equipped with tuyere gasifier which is a device for the gasification of pulverized coal. From the hot blast collector above through the down-flow pipe the hot blast is supplied to tuyere gasifier, in the flow of which pulverized coal is injected. The gases generated in the device are output from the tuyere gasifiers in the area of air tuyere of BF and flow to the combustion zone. The part of oxidative blast supplied directly to BF for coke combustion is supplied by a separate circuit that can be configured in two ways: 1) autonomous vent of hot blast from collector down-flow pipe with its connection to air tuyere for injection into BF; 2) replacement of the part of hot blast with equivalent amount is not heated (cold) oxygen fed by a tube through the tuyere in the combustion zone (PC is supplied by the main channel of the tuyere).

High completeness of gasification of pulverized coal in the tuyere gasifiers at full liquefaction of the ash part with its supply to BF provides an effective mode of coke burning in the combustion zones and allows, in contrast to conventional pulverized coal injection, using a large amount of high-ash coal for the injection to BF.

To analyze the features of the new technology and the expected results the calculations for the model developed in IFM of NASU were performed [1]. The parameters of BF-9 operation at PSC "AMKR" in the best period in terms of parameters – October 2006 – were taken as the base period. The option with PC involves the injection of low-ash coal in the amount of 250 kg/t of pig iron (10% ash, 13% volatile agents, Table 1.) at the full withdrawal of natural gas; the option of PC involves the injection with high-ash coal (25% ash, 25% volatile agents, Table 1.) in the amount of 400 kg of coal per 1 ton of iron, supposing the replacement of the same amount of coke, as in the option with PC.

The other options would minimize the consumption of coke Kmin by increasing the temperature of the blast up to 1300 °C and the transfer of additional limestone from the blast charge to sinter, and the consequent increase in the iron content in the charge and the choice of a rational distribution of the ore load (OL) in cross-section of BF.

The distribution of ore loads on furnace radial circular cross-sections (RCC) is calculated for a given distribution of each component of the charge between the RCC in the base version, and when searching for the best one, they are set. The results of determination of the distributions of relative ore loadings are the following (AOL – actual ore load, EOL – even in intermediate RCCs):

RCC	1	2	3	4	5	6	7	8	9	10
AOL	0.414	1.541	1.475	1.125	1.008	0.995	1.049	0.995	0.961	0.926
EOL	0.42	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12

kg of coal/t of pig iron) it is 342 kg/t. The further improvement of the technology with the injection of CGP will help to achieve minimum

The feature of the distribution of ore loads in the base period (see above) is the presence of individual RCCs with ultra-high load of ore in the intermediate zone, which is indicative for cone loads. However, the location of these RCCs near the axis (RCC-2, 3) significantly changes in the positive direction of their functional role and influence on the efficiency of smelting. This feature requires further study.

Table 2 shows the basic parameters of smelting in a variety of technologies, the figure shows the temperature and concentration field in the volume of BF in these periods. At the injection of PC (250 kg/t of pig iron) the reduction pf coke consumption was 176 kg/t, and taking into account the output of natural gas (87 m^3/t) it was 250 kg/m, which corresponds to an equivalent of substitution (ES_c = 1.0 kg of coke/kg of coal). At the injection of CGP (coal consumption is 400 kg/t) the reduction of cake consumption corresponds to ES_c = 0.54 kg coke/kg of coal. The corresponding equivalents of substitution of carbon coke and coal (see Table 1) are:

- at the injection of PC ES_s = 1.07 kg S_{coke}/kg of S_{coal};
- at the injection of CGP ES_s = 0.794 kg S_{coke}/kg of S_{coal};

The replacement of carbon with the value ES_s> 1.0 kg of S_{coke}/kg of S_{coa}l in case with pulverized coal is completely understandable by the degree of direct reduction, which in its “pure" form comprises 0.03-0.04%/kg of pulverized coal and significantly increases the equivalent of substitution [1]. In the case with CGP the specified value is 0.05%/kg of coal, which corresponds to an increase ES_c by 0.2 kg/kg. Due to this the substitution of carbon could be ES_s = 1.20 vs. actual substitution 0.794 kg of S_{coke}/kg of S_{coa}l. The difference of ES_s= 0.4 kg/kg enables the processes of transforming of the additional flux and slag formed due to excess of coke ash with ash of replacing coal and quantitatively corresponds to the known balance relations [1].

The value of specific consumption of coke at the blowing of pulverized coal (250 kg/t) reduces to 308 kg/t of pig iron, and at blowing of CGP (400 possible level of coke consumption of 200 kg/t of pig iron, which is illustrated by the results of calculation a number of options (Table 2):

- C_{min}AOL is the blast temperature increase up to 1300 °C and transfer of the raw flux from blast charge into the sinter ore at the actual distribution of ore loads at the furnace top (AOL);
- C_{min}EOL+Fe is the same at the even distribution of ore loads in the intermediate radial zones and peripheral funnels (EOL) as well as at the increase of iron content in the burden;
- C_{min}EOL.Fe.CO is the same at the replacement of hot blast with non-heated (cold) oxygen.

The very first option out of the considered gives low coke consumption (250 kg/t) at a moderate performance (9012 tons/day), largely due to good distribution of materials on the furnace top in the base period. Accordingly, for the option C_{min}EOL+Fe the best results were obtained as coke consumption was 199 kg/t of pig iron and the performance was 10078 tons/day. The option C_{min}EOL.Fe.CO (250 kg/m) is also suitable at the definite conditions.

Thus, the charge of 400 kg/t of pig iron of high-carbon (25% of ash) as CGP into the BF will replace the amount of coke that is close to that replaced at the low-ash CGP (10% of ash) injection of 250 kg/t of pig iron. With further improvement of the parameters of the new technology and optimization of distribution of materials on the furnace top it is possible to reduce coke consumption to the minimum permissible level of 180-200 kg/t of pig iron [1].

The change of temperature and concentration zones of furnace chamber during varying the parameters of the new technology is illustrated by the results of calculations given in the Figure below.

As compared to the base period during PC and CGP injection gas isotheres and heat exchange zone boundaries (the points of inflection of temperature difference of gas and burden) are displaced upwards, and the gas and burden temperature difference values increase. SMZ elements are moving upwards as well with some reduction of their thickness.

Table 2. The expected performance of blast furnace smelting in the blast furnace of 5000 m^3 of PJSC "AMKR" with the injection of PC, CGP and unheated (cold) oxygen (CO), as well as minimizing of coke consumption (C_{min}) by increasing the temperature of the blast, the conversion of raw limestone from the blast burden to the sinter burden and the subsequent increase in the iron content in the burden (Fe) and the selection of the distribution of ore loads along the area of furnace top (EOL)

Parameters	**Base**	**PC_{250}**	**CGP_{400}**	**$C_{min}AOL$**	**$C_{min}EOL+Fe$**	**$C_{min}EOL+Fe.CO$**
Daily output, t/day	**9604**	**9170**	**7910**	**9012**	**10078**	**8926**
Coke consumption, kg/t of pig iron	**483**	**308**	**342**	**250**	**199**	**250**
Blast: flow, m^3/min	6674	6389	3060	2172	1488	858
temperature, °C	**1090**	**1090**	**1090**	**1300**	**1300**	**100**
oxygen content, %	**30.5**	**30.5**	**30.5**	**30.5**	**30.5**	**90**
Natural gas consumption, m^3/t	**87**	**0**	**0**	**0**	**0**	**0**
Injected coal consumption, kg/t	**0**	**250**	**400**	**400**	**400**	**400**
Top furnace gas: t, °C	**81**	**308**	**289**	**185**	**62**	**259**
content, %: CO	29.1	27.9	29.3	28.3	26.8	25.9
CO_2	19.8	22.4	19.0	19.9	21.9	20.9
H_2	7.7	5.0	8.3	9.2	9.6	8.5
Limestone/conv.slag, kg/t	35/56	47/56	132/55	0/57	0/54	0/54
Sint.+pellets+ore, kg/t	1629	1627	1610	1677	1566	1567
Iron in burden, %	55.2	55.0	53.5	53.7	57.4	57.4
Ore load, t/t	3.7	5.8	5.4	7.2	8.4	6.7
In slag*, %: silica	37.0	35.9	36.0	35.5	34.3	34.2
alumina	8.7	8.6	9.7	9.5	10.6	10.5
lime	45.0	43.7	43.7	43.2	41.7	41.6
magnesia	4.7	4.5	4.0	4.0	3.9	3.9
Slag quantity, kg/t	**416**	**445**	**550**	**545**	**429**	**429**
Wet gas volume, m^3/t	1715	1649	2027	1720	1538	1774
Oxygen consumption (calc.), m^3/t	141	142	79	49	30	139
Theoretical temp. of combustion, °C	**2219**	**2328**	**2056**	**2054**	**1947**	**1970**
Tuyere gas quantity, m^3/t	1502	1459	1844	1566	1388	1658
Dry BF gas quantity, m^3/t	1607	1568	1905	1598	1411	1646
Direct reduction of Fe oxide, %	**35.9**	**33.1**	**22.0**	**28.3**	**29.0**	**19.1**
$CO+H_2$ usage, %	40.5	44.4	39.1	41.3	44.9	44.7
Lump carbon, kg/t: general/in the area of tuyeres	411/284	262/140	291/185	213/115	170/71	213/134
Total heat gain, kJ/kg	**4425**	**4917**	**5314**	**4617**	**3927**	**4615**
incl.: coke combustion	2790	1374	1815	1131	693	1317
blast and agents heat	**1508**	**3423**	**3373**	**3368**	**3125**	**3191**
Heat consumption, kJ/kg	**3899**	**3846**	**3777**	**3591**	**3346**	**3160**
BF gas enthalpy, kJ/kg	225	824	1164	639	194	1021
Heat losses, kJ/kg	**302**	**247**	**373**	**388**	**387**	**434**
Useful heat quantity, %	88	78	71	78	85	68
Water equivalent ratio	0.856	0.819	0.80	0.831	0.848	0.86
BF gas calorific efficiency, kJ/m^3	4513	4076	4610	4574	4439	4187
Intensity: of gas, $m^3/(m^3 \cdot min)$	2.27	2.09	2.21	2.14	2.14	2.18
of coke/iron ore charge, kg/$m^3 \cdot$day	902/3217	549/3069	525/2620	438/3107	390/3245	435/2876

CGP:** quantity, m^3/t of pig iron	**0**	**0**	**1106**	**1106**	**1106**	**1393**
temperature, °C	-	-	1590	1693	1693	1572
CO+H_2 content, %	-	-	60.3	60.3	60.3	48.1

*** At the following content in the pig iron in all options, %: Si 0.84; Mn 0.32; S 0.019 and slag basicity 1.22.**

**** At the set relation of O/C =0.5 mole/ 0.5 mole**

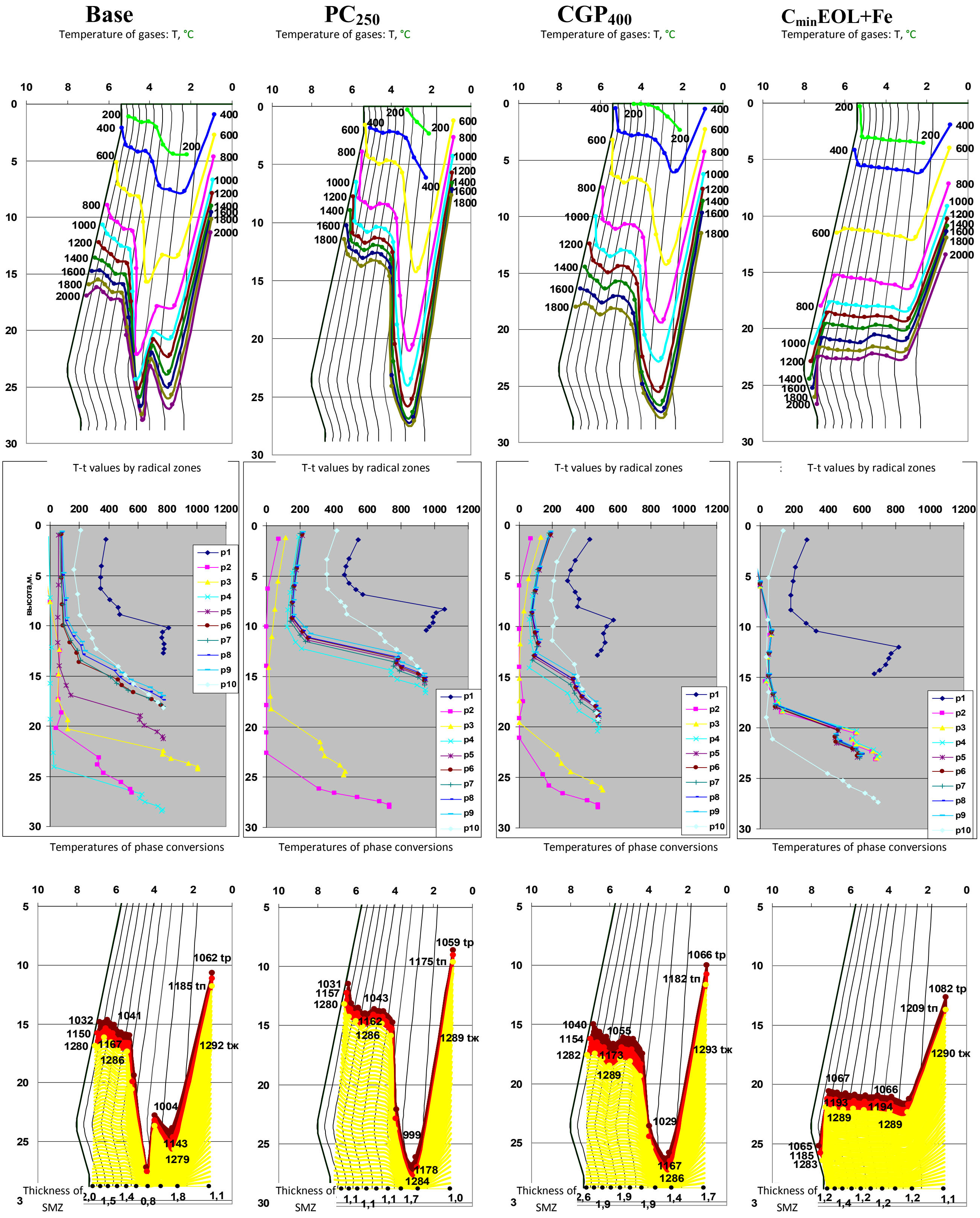

Figure 1. The isolines of the gas temperature (T), the temperature differences between the gas and the charge (T-t), and the parameters of the softening and melting zone (SMZ) in the workspace of BF in the base period, with pulverized coal injection, injection CGP and C_{min}EOL+Fe; horizontal: the distance from the axis of the BF, vertical: the distance from the "technological zero" m. Initial softening point is t_p, melting point is $t_п$, liquid-phase flow - $t_ж$

It is indicative that the values of these changes in case with pulverized coal are significant, and in the case of CGP they are insignificant.

During the formation of the option with minimization of coke consumption the OL value at the periphery at the given OL at the axis and the uniform distribution of the remaining radial zones was varied. In the best of the considered options C_{min}EOL+Fe (199 kg/t of pig iron, 10,000 tons of pig iron per day) there was achieved a uniform temperature distribution in the RCC-2 –9 with the displacement of the isotherms of these RCCs and the heat transfer zones boundaries (the inflection points of the curves of gas and burden temperature differences) in the area below the corresponding values of the base period, as well as peripheral isotherms replacement down the boshes. In accordance with the change of temperature field the SMZ deformation occurred, the elements of which in RCC-2-9 moved to the bottom of the shaft, and in RCC-10 (periphery) – to the middle of the boshes. The temperature-concentration field of furnace chamber obtained in this option is more favourable to the progress of processes than in the other periods.

Conclusions

The analysis of coke-saving modes made on the basis of mathematical modeling of the processes of blast furnace smelting has shown that the implementation of the alternative modes is appropriate to be carried out step by step.

With regard to the BF-9 of PJSC "ArcelorMittal Krivoy Rog" the paramount solution is radical improvement of metallurgical characteristics of coke raw materials, which in the nearest future would help to achieve the coke rate of 380-400 kg/t, and when combined with the developed and mastered technology of loading of lump anthracite into BF it would be 300-320 kg/t without significant capital expenditure.

On this basis in the further period the implementation of substitution technology of more than 50% of the coke with coal at the complete exclusion of natural gas is possible. Since the provision of this technology with low-ash coals in the current and future conditions is problematic, it is necessary to update the development, testing and implementation of a new technology of blast furnace smelting with injection of products of ash coal gasification, which will reduce coke consumption to the lowest possible level of 180-200 kg/t of pig iron.

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Анализ коксосберегающих режимов доменной плавки на примере доменной печи № 9

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На основе разработанной в ИЧМ НАН Украины математической модели выполнен анализ коксосберегающих режимов доменной

плавки, который показал возможность поэтапной реализации альтернативных режимов: загрузка в печь кускового угля с улучшением свойств сырья – использование пылеугольного топлива – вдувание продуктов газификации углей. Такая схема обеспечит сокращение расхода кокса до уровня 200 кг/т чугуна.