CSCanada
Energy Science and Technology
Vol. 6, No. 2, 2013, pp. 1-13
DOI:10.3968/j.est.1923847920130602.2676

ISSN 1923-8460[PRINT]
ISSN 1923-8479[ONLINE]
www.cscanada.net
www.cscanada.org

Substitution of Coke and Energy Saving In Blast Furnaces. Part 5. Problems and Prospects of Low-Coke Blast-Furnace Technology

I. G. Tovarovskiy[a,b],*

[a]Iron and Steel Institute of National Academy of Science, Ukraine.
[b]Academician Starodubov Sqv., Dnepropetrovsk, Ukraine.
*Corresponding author.

Received 20 July 2013; accepted 8 October 2013

Abstract

Two most promising known non-traditional blast furnace technologies can be used to minimize the coke rate: 1) the tuyere injection of the hot reducing gases with removal of CO_2 from the top gas and 100% oxygen blast; 2) 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 (pulverized coal full—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. The advantages of this technology in comparison with traditional PCI injection are as follows: increase in coal rate and decrease in coke consumption; possibility of low grade coals usage; elimination of fine coal grinding; gas desulphurization in the course of coal gasification and the possibility of coal ash fluxing and being removed from the process.

The special compact coal gasifiers attached to the blast furnaces tuyeres were developed and tested at industrial scale. The estimated decrease in coke consumption from 565 kg/thm to 305 kg/thm with injection of 300 kg/thm of coal gasification products and 105 kg/thm of oxygen was specified with respect to operation of blast furnaces at Zaporozgstal Iron & Steel Works (90 years of the last century).

The study by using a multi-zone mathematical model 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 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 (0.65 in the present case).

The application of the developed technology for blast furnaces with burden composition of BF-5 "Severstal" and BF-9 AMKR will allow further decrease in coke rate to the minimal level of 180-200 kg/thm. The payback period of capital investments for this technology is estimated in the range of one year.

Key words: Blast furnace, Coal injection, Reactor-gasifier, Performance improvement, Tuyere, equivalents for replacement, mathematical model, ash fluidization.

I. G. Tovarovskiy (2013). Substitution of Coke and Energy Saving In Blast Furnaces. Part 5. Problems and Prospects of Low-Coke Blast-Furnace Technology. *Energy Science and Technology*, *6*(2), 1-13. Available from: URL: http://www.cscanada.net/index.php/est/article/view/10.3968/j.est.1923847920130602.2676
DOI: http://dx.doi.org/10.3968/j.est.1923847920130602.2676

INTRODUCTION

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 (Puhov, Stepin, & Sceytlin a.o., 1991);

• 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 (article 2 of this thematic selection).

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 proceeded to development, the results of which are set out below.

1. LOW-COKE TECHNOLOGY OF BLAST-FURNACE SMELTING (LCT)

1.1 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 1. 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 a = 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.

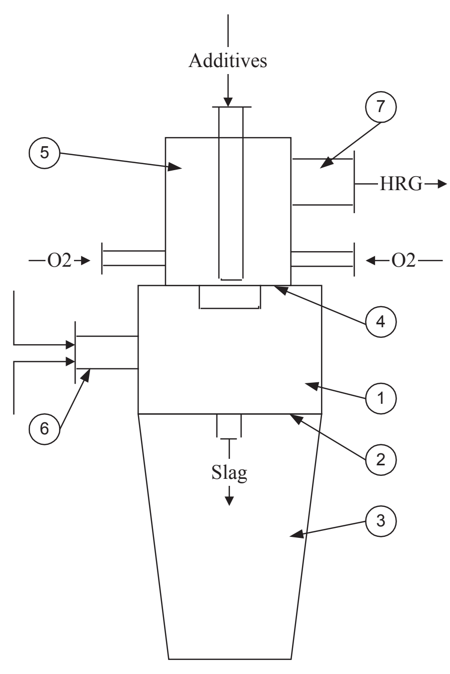


Figure 1
Schematics of Reactor-Gasifier

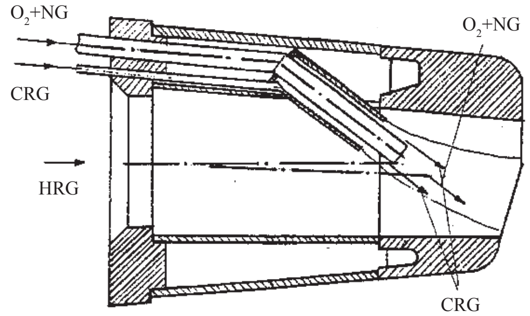


Figure 2
Arrangement of Tuyere for HRG and Oxygen Injection

The other design of the "Tulachermet" tuyere with the oxygen injection into the stream of HRG near the tuyere tip is presented in Figure 3. 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.

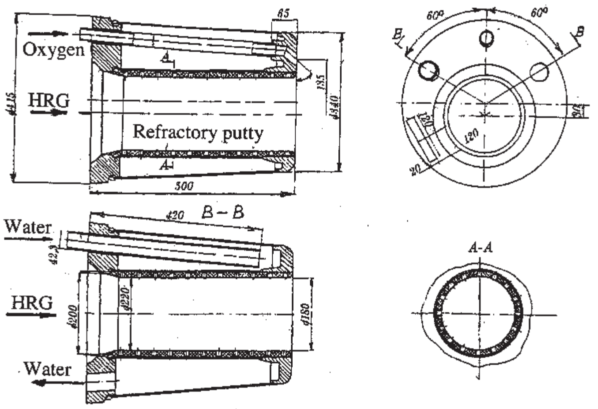


Figure 3
"Tulachermet" Tuyere Arrangement for HRG and Oxygen Injection

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 °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.

1.2 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 4 was tested at the blast furnace at Tulachermet. Figure 5 illustrates the installation of the reactor at blast furnace tuyere.

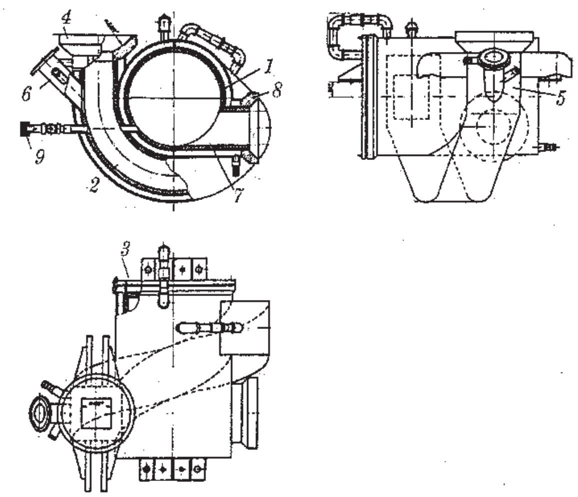


Figure 4
The Tuyere Reactor-Gasifier Tested at Blast Furnace

The TRG (Figure 4) 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.

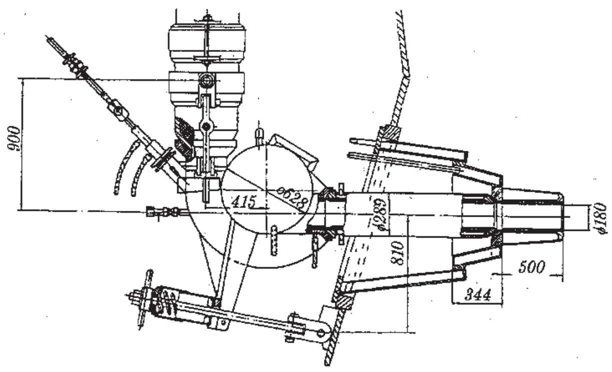


Figure 5
Installation of Reactor-Gasifier at Blast Furnace Tuyere

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 5).

The principle of central reactor-gasifier (FRG) installation for the whole blast furnace is shown in Figure 6.

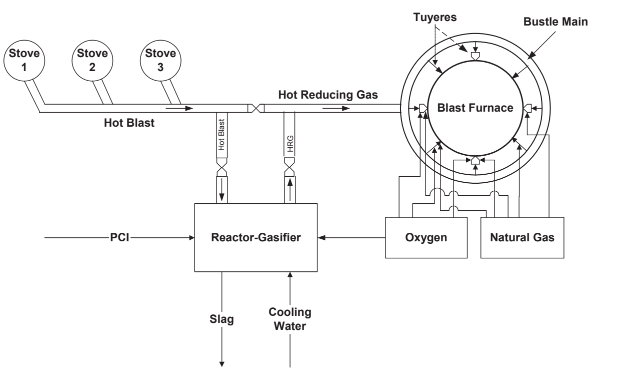


Figure 6
Principle Schematics of Blast Furnace Reactor-Gasifier

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.

2. ESTIMATED RESULTS AND ANALYSIS

The estimated results of Zaporogzstal's Blast furnace #2 operation with FRG are presented in Table 1.

Table 1 results allow to conclude that injection of HRG with temperature of 1200 °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 was 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.

Table 1
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, °C	2039	1900
Blast parameters:		
Blast rate, Nm^3/thm	1271	
Temperature, °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

To be continued

Continued

Parameter	Base case	Trial period
HRG temperature, °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, °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

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 MM 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.

Table 2
Benefits of Blast Furnace Operation With Replacement of Natural Gas With HRG

Parameter	Base case	HRG with T_{blast}=1000 °C	HRG with T_{blast}=1200 °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, °C	1011	1000	1200
RAFT, °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, °C	-	1540	1650
Direct reduction, %	38	30	32
Total RF consumption, kg RF/thm	895.8	798.4	780.4
Top gas calorific value, kg RF/thm	275.1	242.5	229.9
Top gas to external customers, kg RF/thm	165.2	197.5	173.9
Net RF rate for the process, kg RF/thm	730.6	600.9	606.5

2.1 Analytical Study of Blast-Furnace Smelting Technologies That Entail the 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:

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;

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.

2.2 Method of Investigation and Data Source

To systematically evaluate the effect of the main parameters of the technology on blastfurnace smelting indices, we used a mathematical model developed at the Institute of Ferrous Metallurgy (Tovarovsky, 2009; Tovarovsky, Bolshakov, & Merkulov, 2011). 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 No. 5 at the Severstal and the 5OOO-m^3 blast furnace No. 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 3.

Table 3
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

2.3 Analysis of the Research Results

Tables 4 and 5 show the main theoretical indices and parameters of the processes for BF-5 at Severstal and BF-9 at AMKR, respectively. Figure 7 show the corresponding results in graphical form.

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

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

b) 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});

c) 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});

d) 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 c) and d), 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 4
Projected Blast-Furnace Smelting Indices on BF-5 at Severstal (V = 5500 M^3) **With the Injection of PCF, Pgus, and Oxygen** (O)

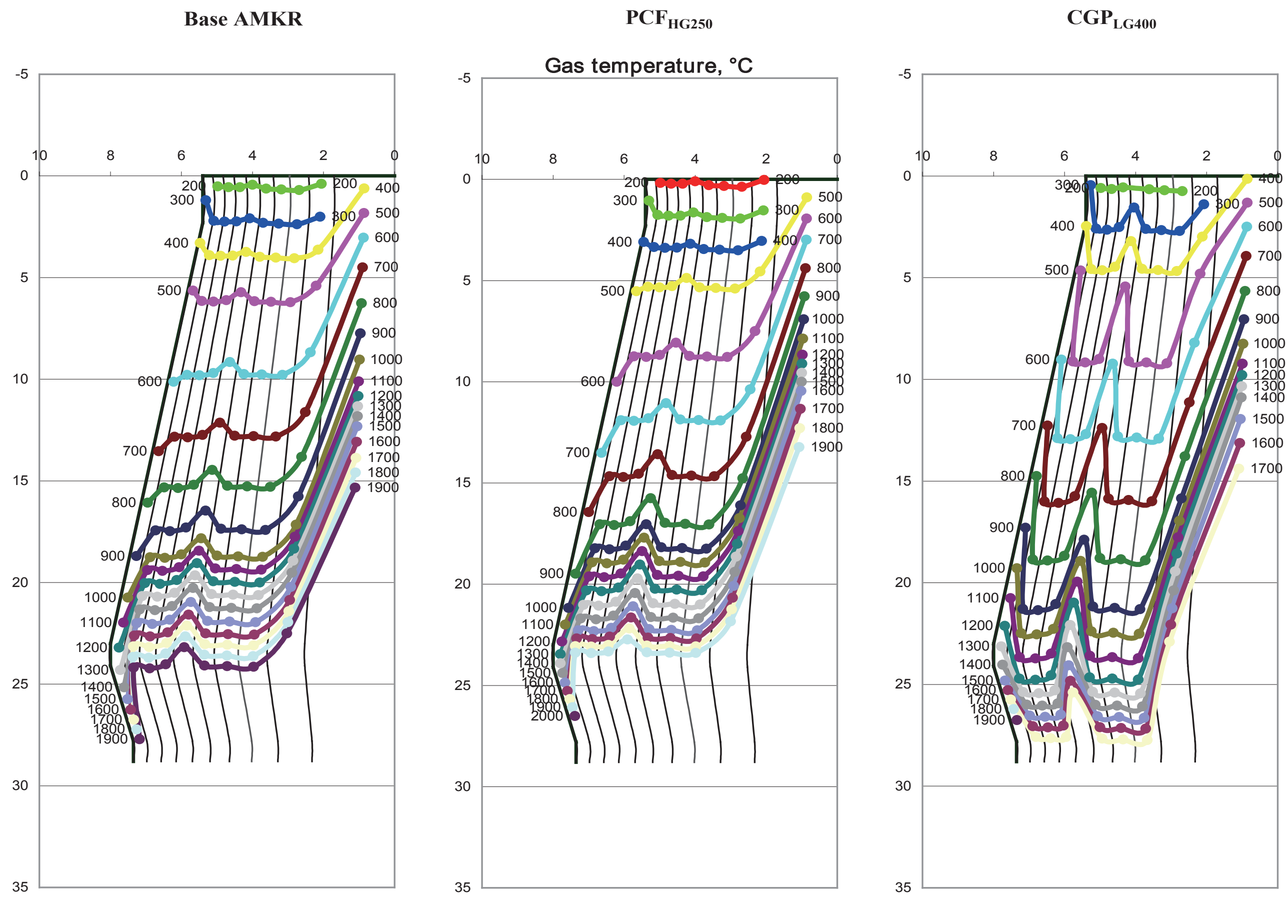
Indices	Base	PCF_{HG250}	PCF_{LG400}	CGP_{LG400}	$CGP_{LG400}O$	CGP_{LG450}	$CGP_{LG450}O$
Unit productivity, tons/(m^3·day)	1.736	1.739	1.533	1.441	1.523	1.373	1.403
Coke rate, kg/ton iron	427	239	240	267	279	249	289
Blast: wind rate, nr/min	7853	6892	6710	2177	879	1719	715
Temperature, °C	1184	1184	1184	1184	20	1184	20
oxygen content, %	24.3	24.3	24.3	24.3	90	24.3	90
Natural-gas consumption m/ton	106	0	0	0	0	0	0
Consumption of injected coal, kg/ton	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, kg/ton	3/5	8/5	78/5	81/5	82/5	92/5	93/5
Sinter + pellets + ore, kg/ton	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, kg/ton	24	21	21	22	22	22	22
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, m^3/ton	1184	1038	1146	396	151	328	133
Volume of moist gas, m^3/ton	1857	1603	1883	2075	1965	2171	2176
Oxygen consumption (calc), m^3/ton	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

To be continued

Continued

Indices	Base	PCF_{HG250}	PCF_{LG400}	CGP_{LG400}	$CGP_{LG400}O$	CGP_{LG450}	$CGP_{LG450}O$
Total heat input, kJ/kg	4524	4483	4804	4971	4845	5093	5098
including: coke combustion	2522	800	947	1197	1597	1041	1449
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/IBC, kg/($m^3 \cdot$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.



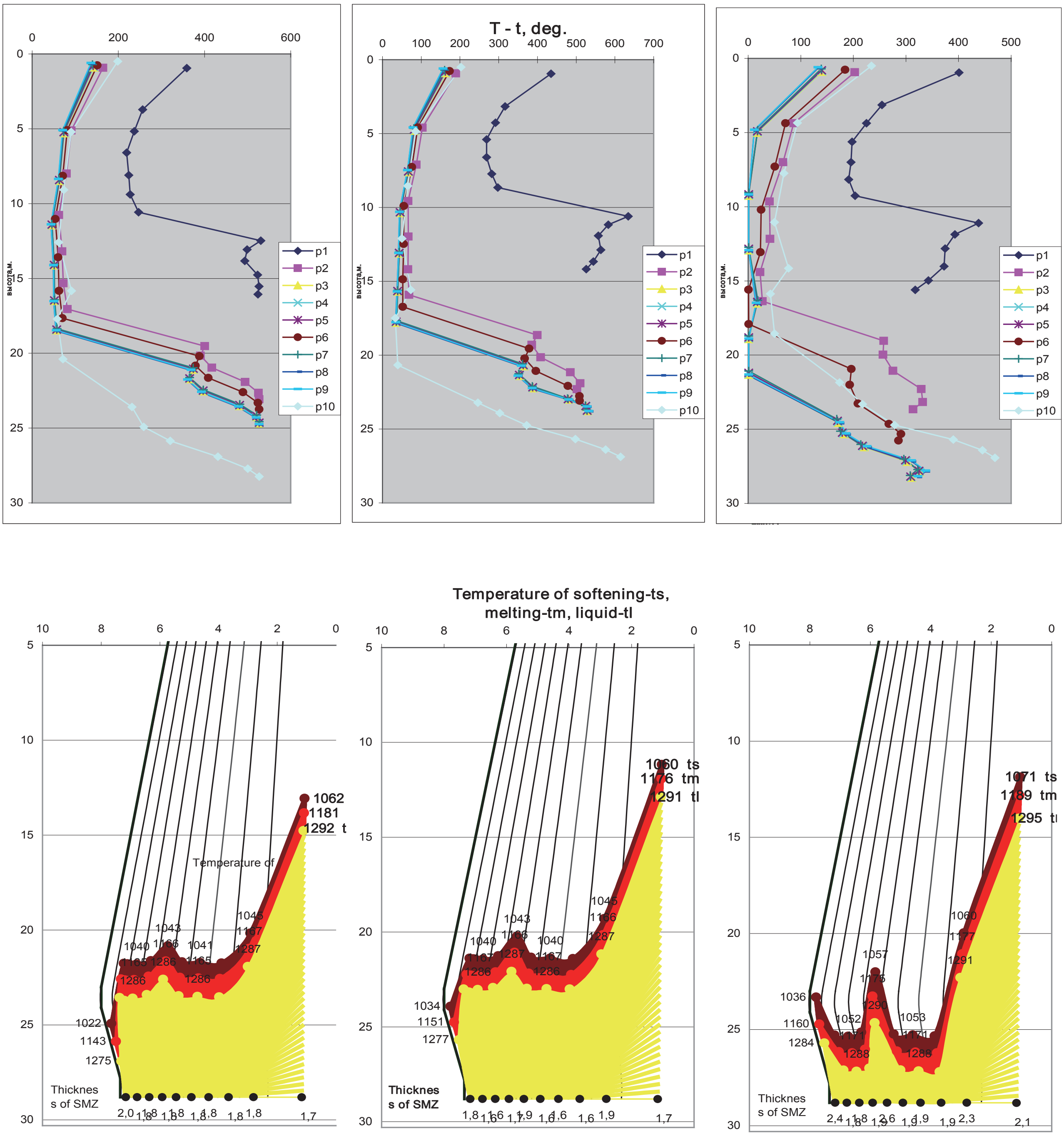


Figure 7
The Temperature Field of the Gas, Difference Between the Gas and Charge Temperatures (T-T) **in the Furnace and the Location of the Softening-Melting Zone** (SMZ). **The vertical distance: from the top; horizontally: from the furnace axis, m**

Table 5
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

To be continued

Continued

Indices	**Base**	**^{PCF}HG250**	**^{PCF}LG400**	**^{CGP}LG400**	**CGP_{LG400}O**	**^{CGP}LG450**
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
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
Indices	**Base**	**^{PCF}HG250**	**^{PCF}LG400**	**^{CGP}LG400**	**CGP_{LG400}-0**	**CGP_{LG450}**
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
Calorific value of top gas, kj/m^3	4140	3783	4238	4091	4913	4162
Rate of:						
Gas use, m^3/(m^3 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

To be continued

Continued

Indices	Base	^{PCF}HG250	^{PCF}LG400	^{CGP}LG400	$CGP_{LG400}O$	^{CGP}LG450
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 (Table 3) 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 6 shows the results of the calculations and the equivalent for the replacement of coke by coal (E_r, kg/kg).

Table 6
Results of Calculations Performed for Four Variants of PCF and CGP Injection on BF-5 at Severstal and BF-9 at AMKR

Indices	PCF_{HG25O}	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	-

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 (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 saved 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 $CGP_{LG450}O$).

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 (Figure 7), and the same tendencies are also seen with the injection of natural gas and coke-oven gas (Tovarovsky, 2009; Tovarovsky, et al., 2011). 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 (Tovarovsky, 2009; Tovarovsky, et al., 2011). 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.

CONCLUSIONS

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

ACKNOWLEDGEMENTS

With special thanks to my colleagues from Iron and Steel Institute of Ukrainian National Academy of Science and professor Gordon I. M. from Hatch, Canada, and also to authors given in the references.

REFERENCES

Puhov, A. P., Stepin, G. M., & Sceytlin a.o., M. A. (1991). *Steel*, (8), 7-13.

Tovarovsky, I. G. (2009). *Blast-furnace smelting* (2nd ed.). Dnepropetrovsk: Porogi. (in Russian).

Tovarovsky, I. G., Bolshakov, V. I., & Merkulov, A. E. (2011). *Analytical study of blast-furnace smelting processes*. Dnepropetrovsk: Ekonomika. (in Russian).