Metallurgist, Vol. 50, Nos. 5–6, 2006

STUDY OF A BLAST-FURNACE SMELTING TECHNOLOGY WHICH INVOLVES THE INJECTION OF PULVERIZED-COAL FUEL, NATURAL GAS, AND AN OXYGEN-ENRICHED BLAST INTO THE HEARTH

A. N. Ryzhenkov, S. L. Yaroshevskii, V. P. Zamuruev, V. E. Popov, and Z. K. Afanas'eva

UDC 669.162.267.4

Studies were made of features of a blast-furnace smelting technology that involves the injection of natural gas (NG), oxygen (O_2) and pulverized-coal fuel (PCF) into the hearth. The technology has been implemented in the compensation and overcompensation regimes, which has made it possible to maintain or improve the gasdynamics of the furnace, the conditions for the reduction of iron oxides, the heating of the charge, and PCF combustion in the tuyere zone as PCF consumption is increased and coke use is decreased. Under the given conditions, with the blast having an oxygen content of 25.64–25.7%, the hearth injection of 131–138 kg PCF and 65–69 m^3 NG for each ton of pig iron has made it possible to reduce coke consumption by 171–185 kg/ton pig (30.2–32.7%), reduce the consumption of comparison fuel by 36–37 kg/ton (5.2–5.3%), and lower the production cost of the pig iron by 43–49 hryvnas/ton (3.7–6.4%). Here, furnace productivity has increased 3.8–6.5%, while the quality of the conversion pig iron remains the same as before. Measures are being implemented to further increase the level and efficiency of PCF use.

The injection of pulverized-coal fuel (PCF) and natural gas (NG) into the hearth of a blast furnace offers several advantages over the injection of PCF alone: the addition of NG creates the conditions necessary to improve the existing smelting technology by optimizing the temperature regime of the hearth, the volume of reducing gases formed, and those gases' hydrogen content. The undoubted advantage of NG remains its purity with respect to its contents of ash, sulfur, and phosphorus.

The first attempts to employ the variant of combination blast just described were made at metallurgical plants in Donetsk (1968–1972) and at Huta Florian (Poland) [1, 2]. The Zaporozhstal' combine and the Donetsk Metallurgical Plant (DMZ) subsequently [3, 4] tried a variant in which PCF and NG were injected simultaneously with the use of an oxygen-enriched blast (this is the technology variant PCF + NG + O_2). Such a combination blast has been successfully introduced at U.S. plants in recent years: in 2000, the method was employed on 10 modern blast furnaces [5].

In 2002, one of the world's first commercial units for preparing NG and injecting it into the hearth of blast furnaces (built at the Donetsk plant in 1980) was rebuilt to reduce the danger of fire and explosion and improve its environmental indices. The unit was provided with modern instruments and automation equipment that have made it into one of the fourth-generation systems now in wide use internationally [6, 7].

Operating the upgraded unit on blast furnace No. 2 (DP-2), the DMZ has continued to refine the practice of injecting PCF and NG into the hearth with an oxygen-enriched blast.

Donetsk Metallurgical Plant and Donetsk National Technical University. Translated from Metallurg, No. 5, pp. 41–44, May, 2006.

TABLE 1. Charge and Performance Indices of BF-2 at the DMZ

Indices	21.12.2002–01.01.2003	02.01.2003–30.03.2003	31.12.2004–07.02.2005	08.02.2005–08.03.2005
1	2	3	4	5
Number of shifts	36	255	109	75
Output of hot pig iron, tons/day/%	2046/100.0	2022/98.8	2178/106.5	2124/103.8
Coke consumption, kg/ton pig	566	470	395	381
Adjusted coke rate (without PCF, NG, or O_2), kg/ton pig	566	471	429	427
Consumption of charge materials, kg/ton pig:				
YuGOK sinter	487	634	709	718
LebGOK pellets	989	909	891	893
scale	6	10	10	8
welding slag	5	8	15	10
limestone	192	188	2	63
soft-burned dolomite (MOD)	0	0	39	49
dolomitized limestone (ChDU)	0	0	98	0
Blast:				
wind rate, m^3/min	2295	2152	1993	1978
pressure, Pa	2.40	2.45	2.45	2.39
temperature, °C	1085	1096	1094	1085
O_2 content, %	22.75	23.10	25.71	25.64
PCF consumption, kg/ton pig	0	96	131	138
Natural-gas consumption, m^3/ton pig	99	62	69	65
Oxygen consumption, m^3/ton pig	37	41	80	81
Top gas:				
pressure, Pa	1.16	1.25	1.21	1.18
temperature, °C	263	272	238	265
composition, %:				
CO_2	15.27	16.16	19.48	20.16
CO	25.68	25.82	23.65	23.93
H_2	6.160	6.130	6.85	6.83
Content in pig, %:				
Si	0.78	0.77	0.77	0.79
Mn	0.24	0.3	0.13	0.12
S	0.035	0.036	0.032	0.035
Content in slag, %:				
Al_2O_3	6.78	6.40	5.85	5.86
MgO	3.42	3.34	7.11	6.27
S	1.78	1.78	1.69	1.71
Slag basicity CaO/SiO_2:				
CaO/SiO_2	1.29	1.27	1.20	1.21
$(CaO+MgO)/SiO_2$	1.38	1.36	1.38	1.37
Slag yield, kg/ton pig	371	389	351	326
Indices of the YuGOK sinter:				
SiO_2, %	10.40	10.15	10.26	10.01
Fe_{tot}, %	54.30	53.95	53.62	54.18
basicity	1.18	1.19	1.22	1.23

1	2	3	4	5
Indices of the LebGOK pellets:				
SiO_2, %	5.68	5.66	5.13	4.93
Fe_{tot}, %	65.98	64.80	65.72	65.73
basicity	0.27	0.27	0.14	0.12
Content in the PCF:				
ash	–	10.23	10.28	9.74
S	–	1.88	1.30	1.39
>80	–	4.32	15.71	18.05
<63	–	92.73	74.89	72.31
Coke quality, %:				
moisture		4.69	4.68	4.87
ash	11.4	11.63	11.80	11.61
sulfur	1.29	1.29	1.37	1.31
M_{25}	85.8	86.76	86.42	86.32
M_{10}	7.78	7.78	7.91	7.66

Compensating measures and the quality of the iron-ore portion of the charge, the coke, and the PCF. The smelting technology that involves the injection of PCF + NG + O_2 was mastered in accordance with the main principles behind the theory and practice of compensating for the adverse effects of burning additional fuel in the tuyere zone and reducing the amount of coke in the charge [8, 9].

To be able to successfully introduce the technology, the following measures were implemented by the plant during the period 2002–2004:

- the percentage of sinter from the Southern Mining-Concentration Combine in the charge was increased;
- manganese-bearing additions were removed from the charge;
- the charge's content of untreated limestone was decreased;
- slag basicity (CaO/SiO_2) was increased to 1.20, mainly by increasing the slag's content of MgO to improve its physical properties;
- slag volume was decreased;
- the amount of process oxygen used to enrich the blast was increased;
- the amount of NG used was decreased;
- the contents of ash and sulfur in the PCF were reduced to the same levels maintained in coke production at the Donetsk Coke and Coal Chemicals Plant;
- the charging system SPCC ↓1.5 m was instituted, this being the optimum system for the given smelting conditions;
- the main smelting indices were optimized in accordance with the recommendations in the "Regime Schedules" [10];
- the nonuniformity of the PCF distribution among the different tuyeres was reduced to ±5–10%.

The quality of the main components of the iron-ore portion of the charge and the coke remained at the previous level (Table 1).

The set of compensatory measures described above and the introduction of 131–138 kg of PCF per ton of pig iron made it possible to reduce coke consumption by 171–185 kg/ton pig; thus, the composite value of the replacement factor K_r was 1.31–1.34 kg/kg. Here, the consumption of comparison fuel decreased by 81–93 kg/ton pig, the production cost per ton of pig iron decreased by 43–49 hryvnas (in February 2005 prices), and furnace productivity increased by 3.8–6.5%

TABLE 2. Integrated Peformance Indices of BF-2 at the DMZ

Indices	21.12.2002–01.01.2003	02.01.2003–30.03.2003	31.12.2004–07.02.2005	08.02.2005–08.03.2005
Unit productivity, tons/m^3·day	1.981	1.957	2.108	2.056
Carbon-based smelting rate, kg/m^3·day	1080	1022	1014	971
Volume percentage of coke in the charge, %	56.405	0.92	46.94	46.54
Yield of hearth gases, m^3/ton	2266	1991	1778	1713
Yield of reducing gases, m^3/ton pig	991	871	856	825
Degree of CO use	0.374	0.390	0.461	0.457
Degree of H_2 use	0.389	0.322	0.405	0.410
Length of time the charge materials were in the furnace, h	6.62	7.29	7.42	7.82
Length of time the gases were in the furnace, sec	2.51	2.89	2.98	3.16
Kulikov's generalized index of slag basicity	1.34	1.32	1.31	1.31
Degree of use of the desulfurizing capacity of the slag, %	45.30	47.04	53.32	49.95
Theoretical combustion temperature, °C	2036	2041	2031	2018
Degree of direct reduction	0.36	0.447	0.316	0.339
Consumption of comparison fuel*, kg/ton pig	701	661	620	608
Coke carbon burnt at the tuyeres, kg/ton pig	354.8	253	208.2	190.8
Coefficient characterizing use of the heat energy of carbon, %	64.37	62.12	71.74	71.66
Heat input to the combustion region, kJ/kg pig	6057.46	5486.80	4939.17	4740.29
Heat of combustion from coke carbon, kJ/kg pig	3475.88	2478.59	2039.81	1868.99
Heat of combustion from PCF, kJ/kg pig	0.00	752.37	957.10	1008.18
Efficiency of heat use, %	77.43	83.11	83.56	85.01
Total heat input, kJ/kg pig	11942.23	11209.74	11122.23	28248.36
Total heat losses, kJ/kg pig	2695.04	1893.27	1827.96	1630.76
Amount of time the reducing gas was in contact with iron oxides, sec	0.262	0.323	0.350	0.378
Production cost of pig, hryvnas/ton (in 2005 prices)	1318.00	1279.00	1275.00	1269.00

* Calculated from the formula: $C_f = (C)Q^p_{Hc}/Q_{eqv} + (NG)Q^p_{Hng}/Q_{eqv} + (PCF)Q^p_{Hpcf}/Q_{eqv}$, where (C), (PCF), and (NG) are the consumptions of coke, PCF, and natural gas in kg or m^3 per ton of pig iron; Q^p_{Hc}, Q^p_{Hpcf}, and Q^p_{Hng} are calculated on the basis of the chemical compositions of the coke, PCF, and natural gas; $Q_{eqv} \approx 29308$ kJ.

(see Table 2, periods 1, 3, and 4). All this shows that at the current stage of its development, PCF technology has been most successfully implemented by using the most favorable regime – the overcompensation regime.

Analysis of composite indices of trial heats conducted with a high PCF consumption. Calculations show that the compensating measures reduced coke consumption by 34–46 kg/ton and allowed PCF to replace 137–139 kg of coke, i.e., the actual value of K_r in the periods being compared was greater than unity. At the same time, the calculated value of K_r in the given periods ≈0.9 kg/kg. Thus, we have proven the hypothesis that when gasdynamic conditions in the furnace become more extreme as a result of the use of low-quality materials in the ore-bearing part of the charge, those conditions can be improved by using an oxygen-enriched blast and injecting PCF in combination with the use of compensating and optimizing measures. Such an approach also improves the descent of the charge and optimizes the gas distribution, which in turn helps conserve coke by allowing for greater use of the reducing potential of the hearth gases (η_{CO}, η_{H2}) and, thus, decreasing the amount of direct reduction of iron r_d that takes place in the furnace [11].

The mechanism by which the existing smelting technology was improved involved several factors: the volume of hearth gases was decreased by 488–553 m^3/ton pig; the length of time the reducing gas was in contact with the iron oxides was increased from 0.262 to 0.378 sec, i.e., more than 40%. That in turn led to a decrease in the coke content of the charge from 56.40 to 46.54% and increased the length of time the charge is inside the furnace from 6.62 to 7.82 h. The end result was qualitative changes in the iron oxide reduction regime: η_{CO} increased from 0.374 to 0.457. Here, the index r_d decreased from 0.36 to 0.316–0.339 – which indicates that the rate of reduction of wustite also increased substantially (see Table 2).

Further evidence of this comes from the indices which characterize the use of heat inside the furnace. For example, the coefficient which characterizes the amount of useful work done by heat increased from 77.43 to 83.56–85.01%, while the coefficient that describes the overall use of heat energy increased from 64.37 to 71.74–71.66%.

One logical consequence of the improvement in the physical properties of the slag and in the reduction reactions and heat exchange inside the furnace was a change in the process of desulfurization of the pig iron: the quality of the pig with respect to sulfur content either decreased or remained the same. However, the generalized index that characterizes basicity (after Kulikov) decreased by 0.03 and slag yield decreased by 20–45 kg/ton pig. These results, equal in importance to the improvement in the slag's physical properties, led to an improvement in the use of the desulfurizing ability of the slag by 4.65–8.02% (see Tables 1 and 2, periods 1, 3, and 4).

The actual values of K_r obtained in the trial heats – which were close to the calculated value – show that the degree of gasification of the PCF in the furnace is high and is close to the limiting value. This was also shown by the experimental data: the injection of PCF into blast furnace 2 (January 2003 – May 2005) did not produce any significant changes in the carbon contents of the top gas or the slag:

	BF-1	BF-2
Total carbon content of the slag, %		
average	0.36	0.40
standard deviation	0.076	0.066
minimum	0.18	0.30
maximum	0.47	0.49
Amount of carbon in the top dust, kg/ton pig		
average	17.79	14.16
standard deviation	5.054	6.546
minimum	10.92	5.61
maximum	29.14	34.28

The following conclusions can be drawn from an examination of the heat balances for the periods that were compared (Table 2): total heat input decreased by 820.2–1067.2 kJ/kg pig when PCF was injected into the hearth in the amount 131–138 kg/ton pig. Here, the amount of heat lost decreased by 867.1–1064.3 kJ/kg pig. Heat input from PCF combustion increased to 957.1–1008.2 kJ/kg pig, but the amount of heat that entered the combustion zone decreased from 6057.5 to 4939.2–4740.3 kJ/ton pig. Thus, the use of PCF and compensating measures decreased the amount of heat supplied by the combustion of the carbon in the coke from 3475.9 to 2039.8–1868.99 kJ/kg pig.

Prospects for the development of PCF technology. Successful use of pulverized-coal fuel in the overcompensation regime confirmed the high degree of efficiency of using PCF under specific smelting conditions at the Donetsk Metallurgical Plant. At the same time, it became evident from this use of PCF that the possibilities of the method are far from being exhausted: there were still high indices for flux consumption, slag volume, and NG use, while the oxygen content of the blast, theoretical combustion temperature, and other parameters remain low (see Table 2). The smelting conditions are also far from the optimum values for $\eta_{CO} = 0.46$ ($\eta_{CO} = 0.56$, according to the foreign literature) and the yield of reducing gases – 825 and 750 m^3/ton pig, respectively.

Taking advantage of the above reserves would make it possible to fully compensate for the changes associated with greater use of PCF. A series of new compensating measures is now being readied for implementation.

However, the quality of the coke still remains an important issue that has yet to be resolved. The DKKhZ (Donetsk Coke and Coal Chemicals Plant) coke used while we were introducing the PCF technology was characterized by low indices for abradability and strength M_{25} and M_{10} (see Table 1). We also periodically determined the CSR index that characterizes the hot strength of coke and found that it was low and unstable (25–45%) for the DKKhZ coke.

The experience of the Baosteel Combine (in China) shows that the injection of 220–260 kg of PCF into the hearth per ton of pig and replacement of 40–50% of the coke by PCF made it necessary to elevate the CSR index to 70–71% [12]. Similar values of the CSR have allowed smelters to successfully introduce a technology that involves a high consumption of PCF on blast furnaces in Germany, Japan, South Korea, and Brazil [5]. It is apparent that in order to further develop PCF technology in Ukraine, it will be necessary to solve the problem of improving the quality and strength characteristics of the coke.

Conclusions. A technology that involves the hearth injection of pulverized-coal fuel, natural gas, and an oxygen-enriched blast was introduced in regimes which exactly compensated and overcompensated for the increased PCF use. As the consumption of PCF was increased and coke consumption was cut back, the use of these regimes made it possible to improve the gasdynamic indices of the furnace, the conditions for the reduction of iron oxide, the heating of the charge, and the combustion of the PCF in the tuyere zone. Under the given conditions, the hearth injection of 131–138 kg PCF/ton pig and 65–69 m^3 NG/ton pig and the use of a blast containing 25.71–25.64% oxygen made it possible to reduce coke consumption by 171–185 kg/ton pig (30.2–32.7%), reduce the consumption of comparison fuel by 81–93 kg/ton (11.6–13.3%), and lower the production cost of the pig iron by 43–49 hryvnas/ton. Here, furnace productivity increased 3.8–6.5% as the quality of the conversion pig iron that was obtained remained unchanged.

REFERENCES

1. G. A. Panev, A. G. Kuzub, P. P. Chuvpylo, et al., “Mastering the operation of equipment and a technology for blast-furnace smelting with the use of pulverized-coal fuel and natural gas,” in: *Metallurgy of Pig Iron* [in Russian], Vol. 18. Metallurgiya, Moscow (1970), pp. 103–110.
2. I. Wanot, W. Matlinski, and I. Kowalczuk, “Snizovani spotreby koksu ve vysokorechim procesu cesou pridavani spolecne fouhaneho uhelneho pvachu a zemniko olynu do histeje vysoke spectrale,” *Mezo-Ved-Techn. Konf.,* Vysokopec, Ostrava, Sb. 4 (1970), pp. 244–256.
3. S. L. Yaroshevskii, A. V. Didevich, A. I. Babich, and V. V. Stepanov, “Study of the condition of pulverized-coal fuel in the hearth of a blast furnace with oxygen enrichment of the blast,” *Stal’,* No. 12, 3–6 (1989).
4. Z. I. Nekrasov et al., “Improving the equipment of a unit for injecting pulverized-coal fuel into a blast-furnace hearth,” *Metall. Gonorud. Promst.,* No. 6 (1970).
5. N. A. Savchuk and I. F. Kurunov, “Blast-furnace smelting at the beginning of the XXI Century,” *Novosti Chernoi Metallurgi za Rubezhom* [in Russian], Chermetinformatsiya, Moscow (2000), Vol. 2.
6. A. N. Ryzhenkov, A. I. Kovalev, S. L. Yaroshevskii, et al., *Blast-Furnace Smelting Technology Involving the Injection of Pulverized-Coal Fuel, Natural Gas, and Oxygen into the Hearth* [in Russian], Novyi Mir, Donetsk (2003).
7. A. N. Ryzhenkov, A. V. Savranskii, S. L. Yaroshevskii, et al., “Blast-furnace smelting technology involving the hearth injection of pulverized-coal fuel and natural gas on an oxygen-enriched blast to replace 30–40% of the coke,” *Metal i Lit’e Ukrainy,* No. 1–2, 3–10 (2005).
8. S. L. Yaroshevskii, *Smelting of Pig Iron with the Use of Pulverized-Coal Fuel* [in Russian], Metallurgiya, Moscow (1988).
9. S. L. Yaroshevskii, V. A. Nozdrachev, A. I. Babich, et al., “Efficiency of using oxygen in blast-furnace smelting and its future prospects,” *Tr. DonGTU Ser. Metallurgiya,* **8**, 39–54 (1999).
10. L. F. Litvinov, A. M. Kuznetsov, V. P. Padalka, et al., “Study and optimization of a technology for blast-furnace smelting,” *Metall i Lit’e Ukrainy,* No. 11–12, 14–19 (2003).
11. V. A. Nozdrachev, S. L. Yaroshevskii, and V. P. Tereschenko, *Promising Blast-Furnace Smelting Technologies That Use Oxygen and Pulverized-Coal Fuel* [in Russian], Novyi Mir, Donetsk (1996).
12. J. Chen, W. Xu, and H. Qian, “Influence of high PCR operation on coke degradation in the blast furnace,” in: *3rd Int Conf. Science and Technolgy of Ironmaking.* Pittsburg, PA, June 16–20, 2003. Dusseldorf, pp. 160–165.