*ISSN 0967-0912, Steel in Translation, 2010, Vol. 40, No. 10, pp. 901–908. © Allerton Press, Inc., 2010.*
*Original Russian Text © A.N. Ryzhenkov, A.A. Minaev, S.L. Yaroshevskii, B.P. Krikunov, V.M. Zamuruev, A.I. Dreiko, 2010, published in "Stal'," 2010, No. 10, pp. 7–13.*

# Coal-Dust Fuel and Blast-Furnace Production in Ukraine

**A. N. Ryzhenkov**[a], **A. A. Minaev**[b], **S. L. Yaroshevskii**[c], **B. P. Krikunov**[a],
**V. M. Zamuruev**[a], **and A. I. Dreiko**[a]

[a]*ZAO Donetskstal'–Metallurgicheskii Zavod, Donetsk, Ukraine*
[b]*Donetsk National Technical University, Donetsk, Ukraine*
[c]*Tekhnopark DonGTTU UNITEKh, Donetsk, Ukraine*

**Abstract**—The possibility of introducing coal-dust fuel at Ukrainian metallurgical plants is considered. The use of coal dust in blast furnaces at rates of 120 kg/t of hot metal immediately reduces coke consumption by 2.7 million t and natural-gas consumption by 1.2 billion m$^3$. In addition, by compensation of the negative impact of coal dust on the technology, the time for conversion to blast-furnace smelting based on coal-dust fuel may be reduced to a year.

**DOI:** 10.3103/S0967091210100098

Ukrainian ferrous metallurgy is responsible for the irrational use of energy resources—primarily coke and natural gas in blast furnaces. Therefore, the consumption of these resources must be considerably reduced in order to improve the profitability of the industry. One option is the use of coal-dust fuel to replace natural gas and a considerable proportion of the coke in smelting hot metal.

In the past 25 years, coal-dust technology has been successfully introduced at 120 blast furnaces, producing hot metal at a rate exceeding 300 million t/yr. As of 2007, coal-dust injection rates of 200–260 kg/t of hot metal had been achieved. Together with other measures, this reduced coke consumption to 240–300 kg/t of hot metal [1–7].

In terms of energy consumption, Ukrainian blast furnaces cannot match global standards: in 2008, the consumption of conventional fuel (including coke) exceeded that of modern foreign blast furnaces by at least 100 kg/t of hot metal (Table 1). Coal-dust injection considerably (by 30–50%) reduces coke consumption, reduces or eliminates natural-gas consumption, and consequently improves the efficiency and competitiveness of Ukrainian ferrous metallurgy.

In Ukraine, work on coal-dust injection in blast furnaces began in 1963 at Donetsk metallurgical plant, on the initiative of N.I. Krasavtsev of Donetsk Scientific-Research Institute of Ferrous Metallurgy [8]. Between 1968 and 1978, experience with coal-dust injection was gained in experiments and industrial trials. In 1980, on the basis of the first European industrial system, a hybrid technology was introduced, with the injection of natural gas and coal-dust fuel by means of an oxygen-rich blast (natural gas + coal dust + O$_2$ technology). This increased the substitution of other fuels for coke from 10–15% to 30–35% [7, 9–11].[1]

## ALTERNATIVES TO CURRENT UKRAINIAN BLAST-FURNACE TECHNOLOGY

We may list the following alternatives to existing fuels.

(1) Natural gas and fuel oil: their widespread industrial adoption is restrained by the minimal reserves and high cost and by their negligible or negative economic impact. A problem with natural gas is the ineffective use of the thermal and reductive potentials of blast-furnace gases, with corresponding increase in conventional-fuel consumption and impairment of coking economics relative to coal-dust fuel, say (Table 1).

In recent years, the efficiency of blast furnaces has fallen dramatically on account of the high cost of natural gas, which considerably exceeds that of coke.

(2) Coke-oven gas: its expediency and efficiency in smelting hot iron has been repeatedly confirmed on an industrial scale around the world [12]. However, current conditions do not support the large-scale industrial introduction of this technology: there is a sharp shortage of coke-oven gas, which is traditionally used very efficiently in the coke industry and metallurgy, as well as the power industry.

Foreign experience shows the expansion of coal-dust injection will be matched by a corresponding

---

[1] Between 1963 and 2005, work was completed on the introduction of coal-dust injection at OAO DMZ, with the assistance of specialists from Donetsk metallurgical plant, Donetsk Scientific-Research Institute of Ferrous Metallurgy, the State Scientific and Research Institute of the Steel Industry, Donetsk National Technological University, the Coal-Chemistry Institute (Kharkov), and elsewhere.

**Table 1.** Efficiency of fuel use in Ukrainian and foreign blast furnaces [1–3, 5, 7, 20]

| Characteristic | For natural gas* | | For coal-dust fuel + natural gas (OAO DMZ, blast furnace 2) | | For coal-dust fuel [1–3, 7, 20] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ukraine | United States (eight furnaces) | | | Belgium, Sidmar Gent, BF-A | France, Arcelor Dunkerque, no. 4 | Germany, Schwelgern no. 1 | Netherlands, Corus Ijmuiden | | China, Baosteel | | South Korea, Posco no. 3 | Japan, Fukuyama no. 3 |
| | | | | | | | | no. 6 | no. 7 | no. 1 | no. 3 | | |
| | 2007 | 2007 | Feb.–March 2005 | December, 2006 | 1997 | 2005 | 1999 | 2007 | 2007 | 2000 | 2003 | | |
| Consumption per 1 t of hot metal: | | | | | | | | | | | | | |
| coke, kg | 505 | 405 | 381 | 430 | 294 | 289.2 | 299 | 260.7 | 276 | 249 | 274 | 271 | 290 |
| natural gas, $m^3$ | 96 | 65.25 | 65 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $O_2$, $m^3$ | 80.4 | 54.06 | 81 | 80 | 60 | 41 | 25 | 129.9 | 101 | 40 | 48 | – | –** |
| fuel oil | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| coal-dust fuel, kg | 0 | 0 | 138 | 174 | 193 | 195.8 | 182 | 238.6 | 224.1 | 260 | 219 | 222.3 | 266 |
| Conventional fuel consumption, kg | 624 | 502 | 607 | 613 | 509 | 507 | 502 | 525 | 524 | 543 | 523 | 523 | 591 |
| Quantity of coke replaced by additional fuel: | | | | | | | | | | | | | |
| kg/t of hot metal | 76.8 | 58.73 | 176.2 | 156.6 | 173.7 | 176.2 | 163.8 | 214.74 | 201.69 | 234 | 197.1 | 200.07 | 239.4 |
| % | 13.2 | 12.7 | 31.6 | 26.7 | 37.1 | 36.3 | 35.4 | 45.2 | 42.2 | 48.4 | 41.8 | 42.5 | 45.2 |

Notes: * Annual mean values of the blast-furnace characteristics.
** A dash indicates that no data are available.

decrease in coke production and hence in the generation of coke-oven gas [11].

(3) Anthracite and thermoanthracite [13, 14]. In the eighteenth and nineteenth centuries, anthracite was used for the production of hot metal, but it was completely displaced by coke, which has undisputed benefits. The use of coke was associated with increase in blast-furnace power and unit volume and improved smelting economics [15–18].

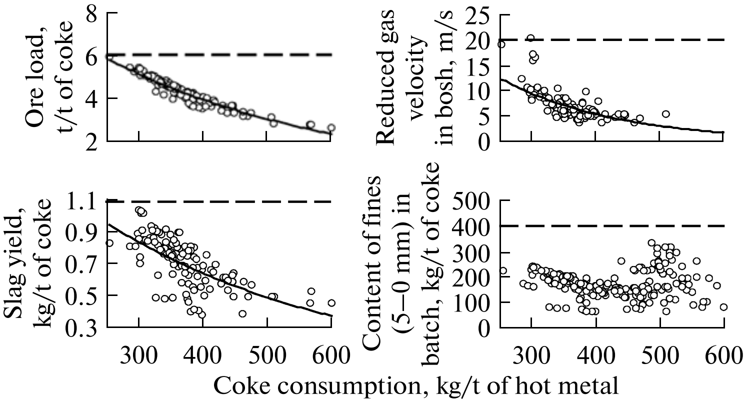
In current conditions, when blast-furnace intensity and productivity are an order of magnitude higher and coke consumption is a third or a half as much as in the nineteenth century, the use of anthracite in place of coke in blast furnaces may only be effective on a very small scale and evidently only in specific conditions: low smelting intensity, the production of special types of hot metal (FeMn, FeSi), etc.

Anthracite reserves are also very limited: no more than 3% of world coal reserves [13, 14].

(4) Preliminary gasification of coal to obtain reducing gases for blast-furnace injection [13, 14]. This notion has certain benefits but is not promising. Even if we assume the creation of reliable equipment—including satisfactory slag removal and the introduction of hot reducing gas in the furnace—we must regard the heat losses as intolerable: in gasification outside the blast furnace, they may amount to 30–50%. These losses are practically absent on gasification within the blast furnaces. All in all, this method is less efficient than coal-dust injection by an order of magnitude.

(5) The use of coal-dust fuel. Since 1983, coal-dust injection has been rapidly introduced at blast furnaces around the world. In 2008, countries such as France, Italy, Spain, Belgium, the Netherlands, Japan, and China used coal-dust injection in practically all hot-metal production [1, 3, 4]. Between 1985 and 1990, practically all new and reconstructed foreign blast furnaces were equipped with coal-dust injection systems.

In 2009, a coal-dust injection system went into operation for four blast furnaces at OAO Alchevskii Metallurgicheskii Kombinat in the Ukraine; the introduction of two more is planned. Thus, by 2011, 13–15 furnaces may operate with coal-dust injection. A benefit of this technology is that it may draw on large fuel reserves: coal-dust fuel may be produced from practically any type of coal, which amounts to more than 75% of all mineral-fuel reserves. This is an order of magnitude greater than the reserves of anthracite and gaseous and liquid fuels.



Dependence of the defining parameters on coke consumption; the dashed lines indicate the threshold values.

Coal-dust injection is based on reliable automated equipment that is environmentally safe and complies with all the requirements of blast-furnace technology.

Finally, the efficiency of coke replacement by coal-dust fuel is found to be 2–2.5 times that for replacement by natural gas, on account of the benefits of carbon injection over hydrogen injection (Table 1) [5, 11]. Theoretical research and industrial experience show that there is considerable scope for further replacement of coke by coal beyond the current level (30–50%), as indicated by the development of programs for the replacement of 60–70% coke by coal-dust fuel in several countries [2].

Hence, coal-dust injection is the most promising for considerable decrease in coke consumption and qualitative increase in smelting efficiency. For the next 20–30 years, this technology will be by far the best option for Ukraine.

## THEORY OF COMPLETE COMPENSATION AND CALCULATION OF BLAST-FURNACE CHARACTERISTICS

The theory of complete compensation of the negative impact of coal-dust injection permits the replacement of trial and error by calculations that take account of the influence of reduction in coke content and coal-dust combustion on smelting. This permits the introduction of optimal and efficient injection conditions in a few months, rather than a few years [5, 8, 11].

Calculation of the smelting characteristics on the basis of complete-compensation theory, with the replacement of up to 50% coke by coal dust is based on work by Ramm [5, 11, 19].

For more reliable calculation of the smelting conditions, we propose defining parameters, with a threshold that cannot be exceeded in practice: the ore load, kg/t of coke; the quantity of fines (5–0 mm) in the iron ore, kg/t of coke; the slag yield, kg/t of coke; the yield of hearth gas, m$^3$/t of coke; the gas velocity in the zone where the batch is plastic, m/s; and the theoretical combustion temperature, °C.

For these characteristics, we analyze annual mean data from 57 blast furnaces in Europe in 2002 and 2004 and 36 furnaces in the United States. It is evident from the analysis (summarized in the figure) that, for the given coke and iron-ore quality and blast parameters, with coke consumption of 250–600 kg/t, there is little likelihood of obtaining a gas velocity in the bosh >20 m/s, ore load >6.0 t/t of coke, hearth-gas yield >5000 m$^3$/t of coke, a content of fines (5–0 mm) in the iron-ore batch >300 kg/t of coke, and slag yield >1000 kg/t of coke. These threshold values of the defining parameters divide the attainable and improbable conditions of blast-furnace smelting with coal-dust injection.

In the analysis of furnace operation and the calculation of the smelting conditions, two stages of coal-dust injection are considered:

(1) coal-dust consumption of 140–150 kg/t of hot metal, which, according to experience at ZAO Donetskstal'–Metallurgicheskii Zavod may be attained by reducing the natural-gas consumption and by means of compensating measures that do not require considerable capital expenditures (improved coke preparation, a system for technological optimization, etc.);

(2) coal-dust consumption of 150 kg/t of hot metal or more, which has been introduced mainly in certain countries in Europe, Asia, and America, on the basis of current batch, technology, and blast-furnace structure.

Software for calculating the smelting characteristics may be written in the Microsoft Access database. Intel Celeron 1200 personal computers (or better) are used for the calculations.

## FIRST AND SECOND STAGES OF COAL-DUST TECHNOLOGY

In 2002, one of the world's first industrial systems for coal-dust injection in the blast-furnace hearth at

**Table 2.** Operational characteristics of blast furnace 2 at ZAO Donetskstal'–Metallurgicheskii Zavod

| Characteristic | December 21 2002 to January 1, 2003 | December 2006 | Prospectively |
|---|---|---|---|
| Proposals* | 1 | 2 | 3 |
| Hot-metal output, t/day | 2055 | 2114 | 2464.4 |
| Productivity, t/$m^3$ day | 1.99 | 2.05 | 2.39 |
| Conventional fuel consumption, kg/t of hot metal | 675 | 596 | 530 |
| Consumption, kg/t of hot metal: | | | |
| skip coke + coke nuts | 564 | 430 | 309.7 |
| coke nuts | 0 | 19 | 50 |
| sinter | 485 | 314 | 314 |
| pellets | 986 | 1235 | 925.1 |
| iron ore | 20 | 0 | 200 |
| iron scrap | 0 | 77 | 77 (60) |
| regular limestone (slightly roasted dolomite) | 192 | 134 | 105.3 |
| Blast: | | | |
| temperature, °C | 1085 | 981 | 1200 |
| pressure, kPa | 240 | 228 | 228 |
| $O_2$ consumption, $m^3$/t of hot metal | 41.5 | 87.5 | 89.6 |
| moisture content, g/$m^3$ | 8.9 | 8.0 | 8.0 |
| coal-dust consumption, kg/t of hot metal | 0 | 174 | 227 |
| natural-gas consumption, $m^3$/t of hot metal | 99 | 0 | 0 |
| Blast-furnace gas: | | | |
| pressure, kPa | 116 | 125 | 125 |
| composition, %: | | | |
| $CO_2$ | 15.3 | 21.4 | 21.9 |
| $H_2$ | 6.2 | 3.9 | 5.6 |
| CO utilization, % | 37.3 | 46.0 | 48.2 |
| Blast-furnace dust, kg/t of hot metal | 35 | 82 | 82 |
| Composition of hot metal, %: | | | |
| Si | 0.78 | 0.70 | 0.70 |
| S | 0.035 | 0.037 | 0.032 |
| Slag yield, kg/t of hot metal | 371 | 373 | 301 |
| Content in slag, %: | | | |
| MgO | 3.4 | 6.4 | 6.1 |
| $Al_2O_3$ | 6.8 | 5.9 | 7.1 |
| Slag basicity (CaO + MgO)/$SiO_2$, units | 1.38 | 1.39 | 1.38 |
| Utilization of slag's desulfurization properties, % | 45.0 | 40.6 | 40.6 |

ZAO Donetskstal'–Metallurgicheskii Zavod (built in 1980) was reconstructed to increase its power and its fire and explosion safety, reduce its environmental impact, and install up-to-date instruments and automatic systems [8–10].

The introduction of the first stage of smelting with coal dust + natural gas + $O_2$ injection at ZAO Donetskstal'–Metallurgicheskii Zavod between 2002 and 2005 complied with the basic theoretical and practical principles of complete compensation. The disruptions introduced by coal-dust injection were compensated by increasing the oxygen content in the blast and reducing the natural-gas consumption; increasing the content of pellets in the batch, in place of fuel sinter from the Southern enrichment facility; reduction in raw limestone consumption; improvement in the characteristics of the coal-dust fuel; and other means.

Thanks to the compensation measures and the injection of coal-dust fuel and natural gas at rates of 138 kg/t of hot metal and 66 $m^3$/t of hot metal, respectively, the first stage of coal-dust technology was operational in January–March 2005 at blast furnace 2, with corresponding reduction in coke consumption by 183 kg/t (32.8%), in natural-gas consumption by 33 $mm^3$/t (~33.0%), in conventional fuel consumption by 93 kg/t, and in the cost of hot metal by 49 hryvnia/t (at February 2005 values); furnace productivity rose by 6.5%. The total replacement coefficient of coke by coal dust is 1.34 kg/kg, which indicates supercompensation [9, 10].

In 2006, at furnace 2, technology with the replacement of natural gas by coal-dust fuel was introduced (Table 2, proposals 1 and 2) [7]. The increase in coal-dust injection to 174 kg/t of hot metal, with appropriate compensation measures, was accompanied by decrease in the natural-gas consumption by 99 $m^3$/t, increase in pellet content in the batch to 73%, slight improvement in quality of the coke and coal-dust fuel, and the introduction of coke nuts in the batch (19 kg/t of hot metal). To ensure the theoretically optimal combustion temperature (104°C), the blast temperature was reduced, but with the maintenance of a high oxygen content (26.2%). The removal of natural gas and the supercompensation were associated with further decreased on the yield of hearth gas (by –594 $m^3$/t of hot metal) and reducing gas (by –225 $m^3$/t), efficient utilization of the reducing potential of CO ($\eta_{CO} = 46.2\%$), maintenance of the high level of direct reduction of iron oxide ($r_d$), and reduction in skip-coke consumption (to 411 kg/t) and in conventional fuel (by 109 kg/t or 17.3%). High thermal efficiency was retained (83.01%).

The furnace productivity was increased by 59 t/day (2.9%). All the defining parameters are below the threshold values, which confirms that the proposed smelting conditions are stable and optimal.

Thus, the partial or complete elimination of natural gas and its replacement by coal-dust fuel (in amounts of 138–174 kg/t in the first and second stages), together with appropriate compensation measures, resulted in increased furnace productivity (by 59–69 t/day, or 2.9–3.4%) and reduced coke consumption (by 134–183 kg/t, or 23.7–32.4%). The replacement of coke by natural gas and coal-dust fuel was increased from 13.9 to 23.7–32.4%. Thus, the use of coal-dust fuel considerably increased the efficiency of blast utilization (by a factor of 100% or more).

Operational experience at ZAO Donetskstal'–Metallurgicheskii Zavod clearly demonstrates that the first stage of coal-dust technology, with coal-dust consumption of 140 kg/t and reduced coke consumption (400 kg/t) is not problematic for Ukrainian blast furnaces. All that is required is to calculate the smelting conditions with coal-dust injection on the basis of Ukrainian and world experience and complete-compensation theory, in the light of the available compensation measures.

On the basis of that experience, the maximum effective coal-dust injection conditions may be calculated for ZAO Donetskstal'–Metallurgicheskii Zavod.

To expand the compensation resources with further increase in coal-dust injection, the following measures have been proposed: increase in blast temperature to 1200°C; production of premium coke (*CSR* > 56%, *CRI* < 30%) rather than regular coke; sifting out of coke nuts from the coke and mixing of the nuts with pellets prior to introduction in the furnace; and reduction in slag yield by replacing some of the sinter with pellets, rich iron-ore pieces, or metal batch. Instead of raw limestone, it is expedient to use roasted limestone or dolomite in the batch (according to experience at OAO Azovstal').

Such compensation measures (mainly organizational measures) do not require major capital expenditures and may be adopted at planned maintenance of blast furnaces 1 and 2 in the coming years. It follows from Table 2 (proposals 1 and 3) that these measures permit increase in coal-dust consumption to 227 kg/t. Together with the elimination of natural-gas injection in the hearth, this reduces the coke consumption to 309.7 kg/t, increases daily furnace output to 2464.4 t (120%), and considerably reduces the costs.

Proposal 3 (second stage of coal-dust technology) is preferable to proposal 1 in terms of reduced yield of slag (by 70 kg/t, or ~19%) and hearth gases (by 902 $m^3$/t, or ~40%), increased blast temperature (by 115°C) and CO utilization $\eta_{CO}$ (by 10.9%, or ~30%), and decrease in the direct reduction of iron oxide ($r_d$).

The viability of stage 2 has been confirmed by recent experience at foreign blast furnaces [1–5, 11]. Currently, coal-dust injection is at levels of 183–265.5 kg/t, with decrease in coke consumption to 249–314 kg/t, high furnace productivity (2.09–3.17 t/$m^3$ day), and high hot-metal quality (Table 3).

**Table 2.** (Contd.)

| Characteristic | December 21 2002 to January 1, 2003 | December 2006 | Prospectively |
|---|---|---|---|
| Yield of hearth gas, $m^3$/t of hot metal | 2282 | 1688 | 1380 |
| Yield of reducing gas, $m^3$/t of hot metal | 998 | 773 | 695 |
| Theoretical combustion temperature, °C | 2040 | 2170 | 2162 |
| Degree of direct reduction, % | 35.0 | 35.0 | 31.6 |
| Thermal efficiency, % | 77.0 | 83.0 | –** |
| Utilization of carbon's thermal energy, % | 64.8 | 62.5 | – |
| Coke content in batch, vol. % | 56.1 | 49.2 | – |
| Residence time of materials in furnace, h | 6.6 | 7.4 | – |
| Defining parameters | | | |
| Ore load, t/t | 2.8 | 3.9 | 5.3 |
| Slag yield, kg/t of coke | 663 | 867 | 972 |
| Yield of blast-furnace gas, $m^3$/t of coke | 4282 | 4297 | 4845 |
| Content of fines in batch, kg/t of coke | 303 | 327 | 436 |
| Gas velocity in bosh, m/s | 8.6 | 10.3 | 19.32 |

Notes: * The figures for proposals 1 and 2 correspond to experimental periods of blast-furnace operation; those for proposal 3 corresponds to calculation.

** A dash indicates that no data are available.

Analysis of the given data and global experience of blast-furnace operation shows that the required level of blast-furnace technology calls for decrease in the yield of blast-furnace gas to 1400–1600 $m^3$/t, reducing gas to 650–700 $m^3$/t, and slag to 219–314 kg/t; reduction in the content of fines in the iron-ore batch to 5%; improvement in *CSR* values of the coke to 60–71%; increase in blast temperature to 1138–1262°C and in theoretical combustion temperature to 2100–2200°C; and the utilization of high-quality coal-dust fuel ($A^c$ = 7.5–8.5%; 0.30–1% S) [1–5, 11].

The calculations show that, for the proposals and situations in Table 3, the defining parameters are below their threshold values, which indicates stable and optimal furnace operation. Coal-dust consumption of more than 200 kg/t is possible thanks to high

**Table 3.** Blast-furnace parameters with high coal-dust consumption [1, 2]

| Melt characteristic | Belgium, Sidmar Gent, 1997 | France, Arcelor Dunkerque | | Netherlands, Corus Ijmuiden | | Japan | | | China, Baosteel | | South Korea, Posco no. 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | no. 8, 2004 | no. 4, 2005 | no. 6, 2005 | no. 7, 2005 | Kakogawa, no. 1 | Fukuyama, no. 3 | Muroran, no. 2 | no. 3, 2003 | no.1 | |
| Situation | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Working volume of furnace, $m^3$ | 1754 | 1335 | 3940 | 2328 | 3790 | 3750 | 2774 | 1963 | 4350 | – | – |
| Productivity, $t/m^3$ day | 2.14 | 2.54 | 2.34 | 3.17 | 2.75 | 1.88 | 1.84 | 2.18 | 2.09 | 2.2 | 2.28 |
| Consumption, kg/t of hot metal: | | | | | | | | | | | |
| reducing agents | 487 | 482 | 485 | 507 | 523 | 545.5 | 554.5 | 505.4 | 492 | 510.6 | 493.3 |
| coke | 294 | 299 | 289 | 274 | 290 | 291 | 280 | 314 | 273 | 249 | 271 |
| coal-dust fuel | 193 | 183 | 196 | 233 | 233 | 254.4 | 265.5 | 191.4 | 219 | 260.6 | 222.3 |
| Moisture content of blast, $g/m^3$ | –* | 7.9 | 15.5 | 8.8 | 9.3 | 17 | 32 | 16.8 | – | 14 | 16 |
| Oxygen content of blast, % | 24.5 | 23.3 | 24.4 | 32.9 | 30.6 | 25.1 | 25.8 | 23.8 | 23.7 | 24.2 | – |
| Blast temperature, °C | 1204 | 1178 | 1181 | 1146 | 1236 | 1233 | 1220 | 1262 | 1248 | 1251 | 1138 |
| Temperature of blast-furnace gas, °C | 130 | 179 | 140 | 118 | 142 | 210 | 251 | – | 157 | 239 | – |
| Degree of gas utilization | 0.501 | 0.518 | 0.496 | 0.493 | 0.471 | 0.496 | 0.65 | 0.96 | 0.503 | 0.51 | – |
| Content in iron-ore component of batch, %: | | | | | | | | | | | |
| sinter | 93.5 | 100 | 77.5 | 44.62 | 46 | 43 | 76.7 | 87.6 | 82.3 | 72.8 | 83.1 |
| pellets | 6.5 | 0 | 9.4 | 52.9 | 50.7 | 35 | 15.5 | 0 | 17.7 | 11.5 | 4.9 |
| Hot-metal temperature, °C | – | 1479 | 1500 | 1503 | 1505 | 1496 | 1501 | 1514 | – | 1501 | 1516 |
| Composition of hot metal, %: | | | | | | | | | | | |
| Si | 0.33 | 0.36 | 0.48 | 0.41 | 0.44 | 0.48 | 0.34 | 0.66 | 0.26 | 0.3 | 0.4 |
| S | 0.031 | 0.013 | 0.019 | 0.032 | 0.032 | 0.021 | 0.027 | 0.015 | 0.02 | 0.021 | 0.017 |
| Slag yield, kg/t | 297 | 308 | 274 | 219 | 236 | 265 | 266 | 309 | 258 | 265 | 277 |
| $Al_2O_3$ content in slag, % | 11.5 | 11.51 | 11.91 | 15.7 | 16.4 | 15.2 | 13.8 | 15.9 | 15.0 | 14.3 | 14.3 |
| Slag basicity $CaO/SiO_2/(CaO + MgO)/SiO_2$ | –/1.44 | 1.2/1.42 | 1.17/1.37 | 1.15/1.47 | 1.15/1.47 | 1.25/– | 1.28/– | 1.26/– | –/1.46 | 1.21/– | 1.25/– |

* A dash indicates that no data are available.

quality of the batch and excellent smelting conditions, with complete compensation of the negative consequences of the coal dust, despite the considerable (up to 50%) decrease in coke consumption.

Thus, global experience confirms that the replacement of coke by coal-dust fuel is superior to the use of any other fuel.

## ECONOMIC EFFICIENCY OF COAL-DUST INJECTION

The efficiency of coal-dust technology may be assessed on the basis of balance calculations and many years of industrial experience at ZAO Donetskstal'–Metallurgicheskii Zavod and abroad (1985–2004) [1–7]. We adopt the following data for the production of hot metal at a rate of 25–28 million t/yr (from 5–6 Ukrainian metallurgical plants): coal-dust consumption 120 kg/t (T coal, with 5–8% ash); reduction in natural-gas consumption 0.4 $m^3$/kg of coal dust; replacement coefficient of coke by coal dust 0.8 kg/kg; cost of coke (at the beginning of 2009) 1000 hryvnia/t; cost of natural gas 2000 hryvnia/1000 $m^3$; cost of coal-dust fuel 700 hryvnia/t.

On that basis, the introduction of coal-dust technology throughout Ukrainian metallurgy would reduce coke consumption by 2.7 million t and natural-gas consumption by 1.2 million $m^3$ and reduce the cost of hot metal by 3.3 billion hryvnia.

The first stage of coal-dust technology will earn back its costs in less than two years. Further increase in the coal-dust consumption and in fuel costs—primarily the costs of natural gas and coke—will correspondingly increase the efficiency of coal-dust technology.

## CONCLUSIONS

(1) Blast-furnace smelting with natural-gas injection in the hearth, which consumes 2.5 billion $m^3$ of natural gas in Ukraine every year, is less efficient than coal-dust injection, in current conditions. The most striking benefit of coal-dust injection is that the quantity of coke that may be replaced by coal dust is double or triple what may be replaced by natural gas.

(2) At present, the conditions for fast and effective introduction of coal-dust technology have been created at ZAO Donetskstal'–Metallurgicheskii Zavod: the necessary equipment has been developed and introduced in industrial conditions; injection of up to 100–170 kg of coal dust per 1 t of hot metal has been successfully introduced, thereby confirming the high economic efficiency of this approach and the possibility of eliminating or considerably reducing natural-gas consumption.

(3) The theory of complete compensation developed at ZAO Donetskstal'–Metallurgicheskii Zavod on the basis of experience with coal-dust technology permits the replacement of trial and error with calculations that take the influence of the reduced coke consumption and coal-dust combustion on the gas-dynamic conditions into account, so that the corresponding disruptions may be calculated and appropriate compensation measures may be adopted. Such quantitative calculations permit faster introduction of optimal blast-furnace conditions with coal-dust injection, in a matter of months rather than years.

(4) In Ukraine, even the first stage in the introduction of blast-furnace smelting with coal-dust injection reduces coke consumption by 2.7 million t and natural-gas consumption by 1.2 billion $m^3$ and lowers the cost of hot metal by 3.3 billion hryvnia, without loss of furnace productivity or hot-metal quality.

The capital costs of the first stage may be earned back within two years.

## REFERENCES

1. Savchuk, N.A. and Kurunov, I.F., Blast-Furnace Production Abroad in the Twenty-First Century, *Novosti chernoi metallurgii za rubezhom* (Developments in Ferrous Metallurgy Abroad), Moscow: Chermetinformatsiya, 2000, vol. 2, appendix 5.
2. Shimizu, M. and Naito, M., Technological Progresses and Researchers in Blast Furnace Ironmaking in the New Century, *Tetsu-to-Hagane*, 2006, vol. 92, no. 12, pp. 694–702.
3. Danloy, G., Midnon, J., Munnix, R., et al., Influence Application of the CRM Blast Modern at Sidmar, *Third International Conference on the Science and Technology of Ironmaking: Proceedings*, Düsseldorf, 2003, pp. 83–88.
4. Shibata, K., Yamagata, Y., Ito, R., et al., Operation of Kakagova no. 1 Blast Furnace with High Pulverized Coal Rate, *First International Conference on Science and Technology of Ironmaking (ICSTI'94): Science and Technology of Ironmaking toward the 21st Century (14–17 June, 1994)*, Sendai International Centers, 1994, pp. 553–558.
5. Yaroshevskii, S.L., Kuznetsov, A.M., and Afanas'eva, Z.K., *Rezervy effektivnosti kombinirovannogo dut'ya v domennykh tsekhakh Ukrainy* (Reserves of Efficiency of Combined Blast in Ukrainian Blast-Furnace Shops), Donetsk: Nord Computer, 2006.
6. Integrated Steelmaking Plants: Danieli Corus and Modern Blast Furnace Technology: First Class Solutions Based on Operational Experience (Danieli Corus, Holland), *2-i Mezhdunar. konf. domenshchikov "Problemy prodleniya kampanii domennoi pechi i osvoeniya tekhnologii vduvaniya PUT. Sovremennye resheniya i prakticheskii opyt"* (Second International Conference of Blast-Furnace Specialists: Extending Blast-Furnace Runs and Introducing Coal-Dust Technology: Current Approaches and Practical Experience), Dnepropetrovsk, 2009.
7. Yaroshevskii, S.L., Popov, V.E., Kuznetsov, A.M., et al., The Importance of Introducing Coal-Dust Technology in Ukrainian Blast-Furnace Technology, *2-i Mezhdunar. konf. domenshchikov "Problemy prodleniya kampanii domennoi pechi i osvoeniya tekhnologii vduvaniya PUT. Sovremennye resheniya i prakticheskii opyt"* (Second International Conference of Blast-Furnace Specialists: Extending Blast-Furnace Runs and Introducing Coal-Dust Technology: Current Approaches and Practical Experience), Dnepropetrovsk: Porogi, 2009, pp. 90–97.
8. Tereshchenko, V.P., History of Coal-Dust Technology at Donetsk Metallurgical Plant: 1963–1006, *Trudy mezhdunar. nauch.-tekhn. konf. "Pyleugol'noe toplivo—al'ternativa prirodnomu gaza pri vyplavke chuguna" (18–21 dek. 2006 g., g. Donetsk)* (Proceedings of an International Conference on Coal-Dust Fuel as an Alternative to Natural Gas in Hot-Metal Production, December 18–21, 2006, Donetsk), Donetsk: UNITEKh, 2006, pp. 13–23.
9. Ryzhenkov, A.N., Yaroshevskii, S.L., Krikunov, B.P., et al., Smelting with Coal-Dust Fuel and Natural Gas in an Oxygen-Rich Blast, *Stal'*, 2005, no. 12, pp. 13–17.
10. Ryzhenkov, A.N., Yaroshevskii, S.L., Zamuraev, V.P., et al., Blast-Furnace Technology with the Injection of Coal-Dust Fuel and Natural Gas in an Oxygen-Rich Blast, *Metallurg*, 2006, no. 5, pp. 41–44.
11. Yaroshevskii, S.L., The Future of Blast-Furnace Technology and the Replacement of Coke by Coal-Dust Fuel, *Trudy mezhdunar. nauch.-tekhn. konf. "Pyleugol'noe toplivo – al'ternativa prirodnomu gaza pri vyplavke chuguna" (18–21 dek. 2006 g., g. Donetsk)* (Proceedings of an International Conference on Coal-Dust Fuel as an Alternative to Natural Gas in Hot-

Metal Production, December 18–21, 2006, Donetsk), Donetsk: UNITEKh, 2006.

12. Pashinskii, V.F., Tovarovskii, I.G., Kovalenko, P.E., and Boikov, N.G., *Domennaya plavka s vduvaniem koksovogo gaza* (Blast-Furnace Smelting with the Injection of Coke-Oven Gas), Kiev: Tekhnika, 1991.
13. Tovarovskii, I.G. and Lyalyuk, V.P., Out of the Frying Pan into the Fire: Transition to Coke-Free Technology in Blast-Furnace Smelting with Complete Replacement of Natural Gas, *Metall. Kompas*, 2009, no. 1, pp. 20–26.
14. Lyalyuk, V.P., Tovarovskii, I.G., Demchuk, D.A., et al., *Koksozameshchayushchie tekhnologii v domennoi plavke* (Coke Substitution in Blast-Furnace Technology), Dnepropetrovsk: Porogi, 2006.
15. Novospasskii, A.F., *Metallurgiya chuguna* (Metallurgy of Iron), Leningrad–Moscow: Gosmashmetizdat, 1933.
16. Pavlov, M.A., *Vospominaniya metallurga* (Memoirs of a Metallurgist), Moscow: Metallurgizdat, 1943.
17. Krasavtsev, N.I., *Metallurgiya chuguna* (Metallurgy of Iron), Moscow: Metallurgizdat, 1952.
18. Pokhvisnev, A.N., Abramov, V.S., Krasavtsev, N.I., and Leonidov, N.K., *Domennoe proizvodstvo* (Blast-Furnace Production), Moscow: Metallurgizdat, 1951.
19. Ramm, A.N., *Sovremennyi domennyi protsess* (Blast-Furnace Processes), Moscow: Metallurgiya, 1980.
20. Naito, M., Recent Progress of Practical BF Operation in Japan and Innovative Trials for the Future, *Fifth European Coke and Ironmaking Congress (12–15 June 2005)*, Stockholm, Sweden, 2005.