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Improvement of Blast Furnace Energy Efficiency by Injection of Preheated Pulverized Coal Fuel with Iron Oxides

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Abstract—This article discusses the improvement methods of blast furnace energy efficiency by combined injection of preheated pulverized coal fuel and iron oxides (concentrates of advanced beneficiation, flue dust, and others) into its tuyeres. The reasonability of the aforementioned measures is substantiated. Based on the overall energy balance, their influence on heat energy parameters of blast furnace smelting has been established including its exergy, environmental, and technoeconomic performances. It has been determined that injection of preheated pulverized coal fuel into blast furnace well together with constant temperature of the tuyere area allows to increase the furnace output by at least 0.3% per each 100°C increase in the temperature of pulverized coal fuel, to decrease coke consumption by about 3%, and to increase exergy efficiency by up to 0.2%. Favorable influence of injection of pulverized iron oxides into blast furnace well of blast furnace on heat and gas dynamic operation of the furnace are demonstrated.

Keywords: blast furnace, preheating of pulverized coal fuel, pulverized iron oxides, overall energy balance, heat exchange, output, coke consumption, exergy, environmental performances

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Searching for resources of improvement of blast furnace (BF) operation efficiency accompanied by the use of pulverized coal injection (PCI) is an urgent issue. A promising approach to solution to this problem is preheating of PCI and its injection together with pulverized iron oxide (FeO, Fe_3O_4, Fe_2O_3) [1–3].

In order to study the influence of the mentioned approaches on heat energy parameters, exergy, environmental, and technoeconomic performances (TEP) of BF operation, as well as to determine rational energy efficient modes of furnace operation, the overall energy balance of BF smelting was developed including the set of material, heat energy, and exergy balances [4–6] (Fig. 1).

In the case of injection of cold PVF into BF well, additional energy inputs are required for heating this fuel in the furnace. With the aim of minimizing such expenses, it is proposed to preheat PCI. The economic effect of injection of preheated PCI into BF is achieved by introducing additional physical heat, increasing the completeness of fuel combustion, decreasing external heat losses and coke consumption for their compensation [7–9].

Based on overall energy balances of BF smelting, the influence of PCI preheating on changes in heat operation of the furnace was estimated including its TEP with consideration of external heat losses in cooling system. The heat balance was based on the best operation period of BF No. 4 (capacity: 1513 m^3), PAO Zaporozhstal with maximum consumption of the injected PCI and output at minimum coke consumption and the following furnace process variables: blast flow rate of about 3000 nm^3/min; oxygen concentration in blast: 23–24%; blast temperature (R_{blast}): 1100–1150°C; PCI consumption: 19–24 t/h; steam flow rate for blast moisturization: 0.1–0.5 t/h; ore burden on coke: 4.3–4.9 t/t coke; iron content in furnace charge: 55–56%; heat losses in cooling system: 10–15 MW.

The influence of injection of PCI preheated to 400°C into BF well on the performances of BF heat operation was estimated for the two cases:

— heating and equal PCI consumption, other conditions being equal (Fig. 2);

— PCI heating and maintaining of constant temperature of tuyere area due to increased PCI consumption (Fig. 3).

The performed analysis demonstrated that the decreased consumption of coke, fuel equivalent and increase in furnace output upon injection of preheated PCI into BF well is achieved by the increase:

— by 0.3–0.4% of the average fuel heat utilization factor (FHUF) in furnace process areas due to the additional amount of physical heat;

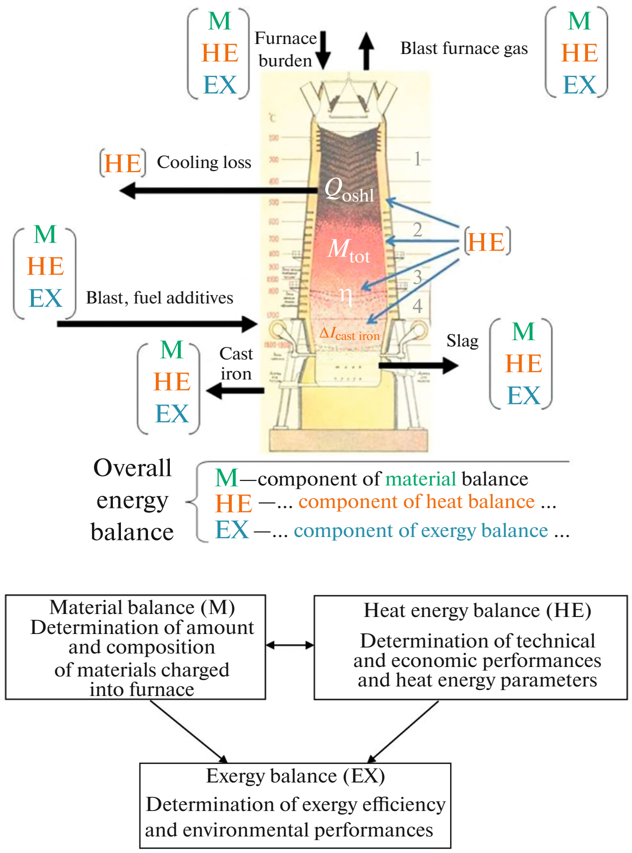

Fig. 1. Flowchart of overall energy balance of blast furnace smelting (a) and description of constituents (b); heat energy performances [7]: Q_{oshl}—heat losses of furnace operation space, MW; M_{tot}—total heat capacity, MW; η—average coefficient of fuel heat utilization (CFU), fractions; ΔI_{cast}—heat deficit of cast iron, MJ/t cast iron.

— by 1–2 MW of the assimilated heat power in furnace process areas due to increase in FHUF;

— by 0.5% of the extent of direct reduction of iron due to additional heat and increase in the assimilated heat power.

Increase in heat supplied to BF well, resulting in an increase in the level of assimilated heat power in the furnace process areas, promotes the progress of direct reduction, thus increasing the furnace output (due to increase in cast iron amount produced from iron reduced by solid carbon and carbon oxide evolved upon direct reduction of iron). Injection of preheated PCI into BF well leads to temperature increase in the tuyere area (by 15°C per each 100°C of increase in fuel temperature). Increase in consumption of preheated PCI allows to maintain the temperature of the tuyere area at constant level.

Analysis of injection of preheated PCI into BF well at constant temperature of the tuyere area demonstrated that the furnace output increases by 0.3% and higher per each increase in PCI temperature by 100°C, which is accompanied by decrease in coke consumption (by about 11 kg/t of cast iron, that is, 3%), and the extent of direct reduction of iron decreases (to 0.2%) (Fig. 3). It should be mentioned that the furnace output upon injection of preheated PCI into BF well while maintaining constant temperature of tuyere area increases less intensively, and the coke saving is more significant than in the case of only PCI preheating. Weak increase in the furnace output is related with

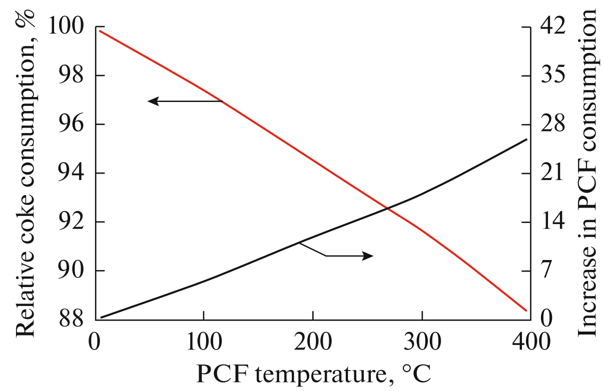

Fig. 2. BF output and coke consumption as a function of PCI temperature at constant PCI consumption, other conditions being equal.

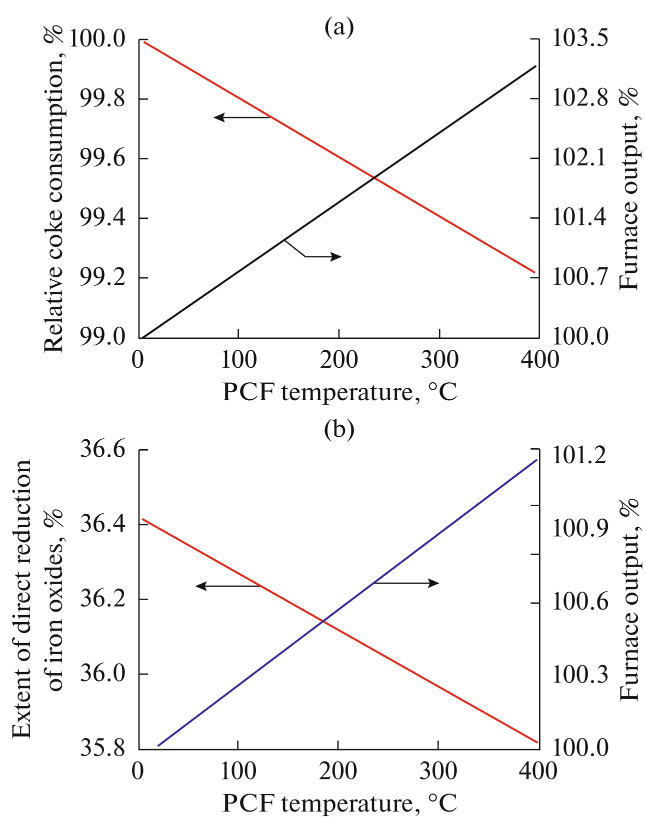

Fig. 3. Coke consumption (a) and BF output (b) as a function of PCI temperature and amount at constant temperature of tuyere area.

Table 1. Influence of PCI heating on exergy and environmental performances of blast furnace*

Performance	Units of measurement	PCI temperature, °C				
		basic	100	200	300	400
Cumulative exergy input	GJ/t	19.52	19.45 / 19.49	19.38 / 19.46	19.31 / 19.41	19.23 / 19.37
Cumulative exergy of smelting products	GJ/t	16.77	16.74 / 16.78	16.72 / 16.78	16.69 / 16.78	16.66 / 16.79
Exergy loss	GJ/t	2.75	2.71 / 2.72	2.66 / 2.67	2.62 / 2.63	2.57 / 2.58
Exergy efficiency:						
Thermodynamic perfection of blast furnace process	%	85.9	86.1 / 86.1	86.3 / 86.3	86.4 / 86.5	86.6 / 86.7
Process efficiency	%	46.1	46.2 / 46.1	46.4 / 46.2	46.6 / 46.3	46.8 / 46.4
Generalized efficiency of cast iron production	%	56.1	56.4 / 56.3	56.6 / 56.5	56.8 / 56.7	57.1 / 56.9
Environmental performances:						
Environmental intensity	Fractions	0.07	0.07 / 0.07	0.07 / 0.07	0.07 / 0.07	0.07 / 0.07
Resource intensity	Fractions	1.28	1.28 / 1.28	1.27 / 1.27	1.27 / 1.27	1.27 / 1.27
Eco-factor	Fractions	0.73	0.73 / 0.73	0.73 / 0.73	0.73 / 0.73	0.73 / 0.74

* Numerator: at varying temperature of tuyere area; denominator: at constant temperature of tuyere area.

injection of additional PCI, which decreases average FHUF and power assimilated in different furnace areas, thus allowing to increase hydrogen content and portion of furnace output obtained indirectly as well as to save more coke.

Analysis of the influence of heated PCI on exergy and environmental performances of furnace operation evidences that when the exergy efficiency [10] increases by ~0.2% per each increase of PCI temperature by 100°C, the energy loss decreases by nearly 2%, and the environmental performances [10] remain at previous level (Table 1).

Nowadays, the PCI consumption at Ukrainian metallurgical companies approaches 200 kg/t of cast iron. Increase in this performance leads to an increase in ore burden on coke in BF and, as a consequence, deterioration of gas permeability of layers of furnace charge in dry area, which influences negatively on progress of the heat exchange and reduction process [1–3, 11].

Another promising measure, which would allow to improve the efficiency of PCI technology in BF process, is injection of iron ore stuff with high iron content into BF well. According to the data in [11, 12], injection of iron ore stuff into BF well allows to equalize the ratio of coke and iron ore layers (to decrease ore burden on coke in the furnace charge), thus increasing gas permeability of the charge column (due to decreased content of fines). The economic effect of this measure is that upon such utilization of iron ore materials, the metallurgical plant does not spend money for their agglomeration.

Implementation attempts of combined injection of PCI and pulverized iron containing material by the companies in France and Japan were aimed at the reduction of silicon content in cast iron [12]. While analyzing the influence of injection of pulverized iron oxides on the performances of BF heat operation and determination of its exergy and environmental performances, several variants were considered for maintaining constant temperature of the tuyere area during injection of pulverized iron oxides into BF well in amount of up to 250 kg/t (Table 2):

— upon separate injection of oxides FeO, Fe_3O_4, and Fe_2O_3 and maintaining constant temperature of tuyere area by injection of additional process oxygen (variant No. 1);

— upon injection of FeO and maintaining constant level of temperature of tuyere area, coke consumption,

Table 2. Influence of injection of pulverized iron oxides on performances of heat operation of blast furnace

Furnace performance	Variant				
	1			2	3
	separate injection of FeO, Fe_3O_4, and Fe_2O_3 while maintaining constant temperature of tuyere area[2]			injection of FeO while maintaining constant temperature of tuyere area, coke consumption, and ore burden[2]	replacement of a portion of sinter burden charged by furnace throat with injected iron oxides while maintaining constant temperature of tuyere area and coke consumption[2]
Type of injected oxide	FeO	Fe_3O_4	Fe_2O_3	FeO	FeO
Variables[1]:					
output	+3	+2–2.5	+2	+2.6	+2.5
coke consumption	+2–3			Constant	Constant
consumption of fuel equivalent	+ 1			+1	+1
ore burden	–2.4	–1.8	–1.4	Constant	–1
gas permeability	Increases			Does not change	Increases
extent of direct reduction of iron oxides (rd)	–1			–1	–1
blast furnace gas yield	–1			–1	–1
heat of combustion of dry blast furnace gas	–1–3			+2–3	+ 2–3
yield of secondary energy resources (SER)	+ 1–5			+2–3	+2–3
Exergy efficiency					
thermodynamic perfection of blast furnace process	–0.3–0.7			–0.3–0.4	–0.3–0.4
process efficiency	–0.3–0.6			–0.3–0.4	–0.2–0.4
generalized efficiency of cast iron production	–0.2–0.4			–0.1–0.2	–0.1–0.2
Environmental performances[3]:					
environmental intensity	0.07–0.05 (–)			0.07–0.05 (–)	0.07–0.05 (–)
resource intensity	1.26–1.40 (+)			1.26–1.33 (+)	1.26–1.33 (+)
eco-factor	0.74–0.68 (–)			0.74–0.71 (–)	0.74–0.71 (–)

[1] Changes of all variables are shown in percent per each additional percent of O_2 in injection; [2] Due to injection of additional technological oxygen and PCI; [3] Change ranges of environmental performances are shown for different variants of injection of iron ore oxides while maintaining constant temperature of tuyere area; "+" denotes increase; "–" denotes decrease in the performances.

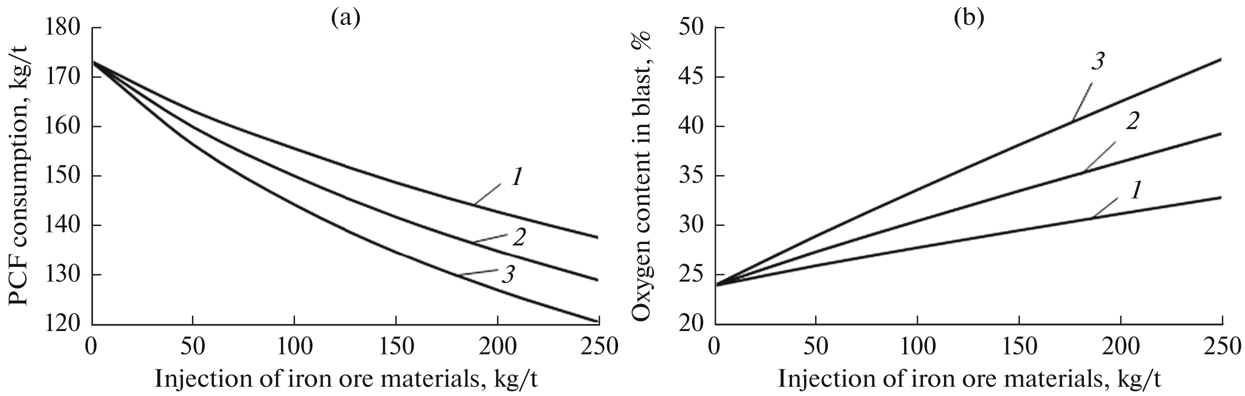

Fig. 4. PCI specific consumption (a) and oxygen content in blast (b) as a function of iron oxides (*1*—FeO, *2*—Fe_3O_4, *3*—Fe_2O_3) while maintaining constant temperature of tuyere area.

and ore burden by injection of additional process oxygen and PCI (variant No. 2);

— upon substitution of a portion of sinter burden, charged by furnace throat, with pulverized FeO injected by tuyeres, maintaining constant temperature of tuyere area and coke consumption by injection of additional process oxygen and PCI (variant No. 3).

Since injection of pulverized iron oxides results in a decreased temperature of the tuyere area, then in order to maintain it at constant level it would be reasonable to increase oxygen concentration in blast. The results of analysis demonstrated that injection of FeO, Fe_3O_4, and Fe_2O_3 in BF well exerts favorable influence on the performances of heat and gas dynamic operation of the furnace, providing new opportunities for improvement of BF smelting. For instance, at constant consumption of PCI equaling to 23.5 t/h and constant temperature of tuyere area due to increase in oxygen concentration in blast, the injection of iron oxides would allow (Fig. 4 and Table 2, variant 1):

— to increase furnace output (for injection of FeO: by 3%, for Fe_3O_4: by 2–2.5%, for Fe_2O_3: by 2%);

— to decrease ore burden in furnace dry area (for injection of FeO: by 2.4%, for Fe_3O_4: by 1.8%, Fe_2O_3: by 1.4%), thus increasing gas permeability of this area;

— to decrease the extent of direct reduction by 1% (due to decrease in the content of non-reduced iron);

— to increase the flue gas yield by 1% (due to increase in the yield of CO and H_2), heat of combustion of dry flue gas by 1–3% and the yield of secondary energy resources by 1–5%;

— to decrease the coefficient of environmental intensity, that is, to decrease the level of negative environmental impacts of specific emissions and their constituents.

Injection of pulverized iron oxides into BF while maintaining constant temperature of the tuyere area by injection of additional process oxygen leads to increased coke consumption (Table 2, variant 1). In order to retain the coke consumption at previous level, it is proposed to inject an additional amount of PCI (Table 2, variants 2 and 3).

A decrease in exergy efficiency, an increase in resource intensity and a decrease in eco-factor with increase in consumption of pulverized iron oxides are related with increased consumption of coke, PCI, as well as heat of combustion of flue gas. One of the advantages of BF operation during substitution of a portion of charged sinter burden by injected pulverized iron ore materials is a decrease in ore burden on coke in furnace dry area, allowing to increase gas permeability of this area (Table 2, variants 1 and 3).

The obtained results of heat energy analysis upon injection of iron ore stuff demonstrated good agreement with analytical and practical results of foreign researchers regarding furnace output, coke consumption, extent of direct reduction, and flue gas yield (Fig. 5).

The influence of injection of pulverized iron oxides on the temperature of the tuyere area are in sufficient correlation with the data in [11, 12]. The differences can be related with dissimilar composition of injected materials and the use of different equations for calculation of theoretical combustion temperature (Fig. 6).

CONCLUSIONS

(1) This article demonstrated promises of improvement of BF smelting with the injection of preheated PCI together with oxidized iron (concentrated products after advanced beneficiation, flue dust) and oxygen into BF well.

(2) Based on the overall energy balance of BF smelting, technical and economic substantiation is given for reasonability of PCI preheating prior to its charging into BF and injection of pulverized iron oxides FeO, Fe_3O_4, Fe_2O_3 into BF well. The relevant regularities are clarified and the influence of these measures on the performances of heat operation of BF

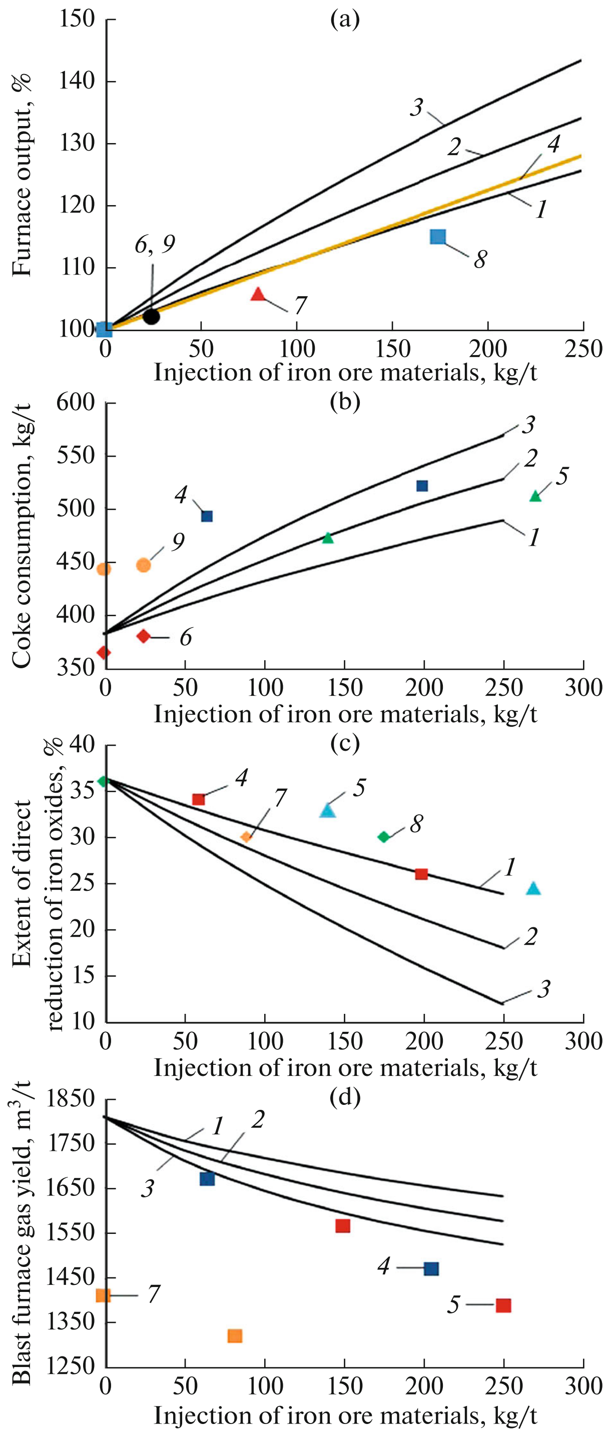

Fig. 5. Furnace output (a), coke consumption (b), extent of direct reduction (c), and yield of dry blast furnace gas (d) as a function of injection of iron ore materials: *1–3*—according to heat energy model (*1*—FeO, *2*—Fe_3O_4, *3*—Fe_2O_3); *4*, *5*, *10*—according to simulation by Japanese researchers [12] (*4*—T_{blast} = 1100°C, *5*—T_{blast} = 1350°C); *6*—operation practice of BF No. 2 in Dunkirk (France) [12]; *7*, *8*—simulation results by Schneider [12] (*7*—ore injection, *8*—injection of metallized ore); *9*—operation practice of BF No. 1 in Solmar (France) upon injection of aqueous ore slurry containing 85% of disintegrated ore [12].

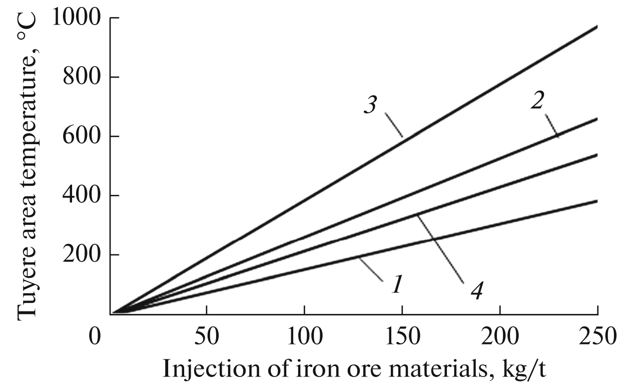

Fig. 6. Temperature of tuyere area as a function of injection of iron ore materials: *1–3* according to heat energy model (*1*—FeO, *2*—Fe_3O_4, *3*—Fe_2O_3); *4*—according to experimental data by Gudenau [11].

are quantitatively estimated including exergy and environmental performances.

(3) It has been established that injection of preheated PCI into BF well while maintaining constant temperature of tuyere area allows to increase the furnace output by at least 0.3% per each 100°C increase in the temperature, to decrease coke consumption by about 3%, and to increase exergy efficiency by up to 0.2% together with constant level environmental performances.

(4) While maintaining a constant level of the tuyere area temperature, coke consumption, and ore burden by means of injection of process oxygen and PCI, the injection of pulverized iron oxides allows to increase the furnace output by 2.6% per each additional percent of O_2 in blast (due to oxygen enrichment), to retain rational values of ore burden in furnace dry area, gas permeability of this area, and specific coke consumption by injection of additional content of PCI, to decrease the extent of direct reduction (by 1% per each percent of O_2) due to reduction of content of nonreduced iron, to increase the output of flue gas (by 1%) and secondary energy resources (by 2–3%), to increase the heat of combustion of flue gas (by 2–3% per each percent of O_2), as well as to decrease harmful environmental impact of BF smelting.

(5) A promising trend to improve environmental performances of BF smelting is the combined injection of PCI with flue dust, which can contain more than 40% of iron and 20% of carbon.

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