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Possibilities for Normalization of the Gasdynamic Mode of Blast Melting with Pulverized Coal Injection

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Abstract—When a blast furnace with a volume of 5000 m^3 was transferred to pulverized coal injection technology, an intense peripheral gas flow, which led to the combustion of shoulder and tuyere coolers, developed. It was not possible to eliminate this phenomenon either by methods of control "from above" or by reducing the diameter of tuyeres. To eliminate the peripheral gas flow, it is advisable on a furnace with a hearth diameter of 14.7 m to maintain the total mechanical energy of the combined blast flow at the tuyere cut at a level not lower than 2100–2600 kJ / s, and the total mechanical energy of the hearth gas flow not lower than 5100–5300 kJ /from. It is also necessary to form a narrow coke "vent" on the top of the blast furnace and to stretch the ore ridge as much as possible.

Keywords: blast-furnace smelting, pulverized coal fuel, blast energy parameters, furnace charging modes
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The transition to pulverized coal injection (PCI) into the blast furnace always causes an increase in the peripheral gas flow. Indeed, there are many reasons for this, and all of them are adequately covered in the literature. However, the phenomenon of the extreme peripheral gas flow in the tuyere region with a sharp increase in the heat load on the shoulder coolers, which was observed in some blast furnaces during the transition to PCI technology, still has no unambiguous interpretation. Blast furnace no. 9 with a volume of 5000 m^3 at PJSC ArcelorMittal Krivoy Rog (AMKR) [1–4], where measures are taken that only exacerbate the problem due to obviously erroneous explanations of the reasons for this phenomenon, is a prime example.

PCI technology at blast furnace no. 9 at AMKR was first used in January 2016. The main developer of the system was Danieli Corus. Its specialists accompanied the development of this technology at the blast furnace, which was reported at the International Scientific and Production Conference, Experience in the Implementation and Solutions to the Problems of the Development of PCI technology in Blast Furnace Production (Krivoy Rog, AMKR, May 12–13, 2016).

Technological and especially technical problems began to haunt the blast furnaces of this furnace from the first days of PCI. During the start-up period of mastering this technology, cases of burning of refrigerators of the cooling system, as well as failure of air tuyeres due to burnout and deformation due to frequent slippage of an unstable skull, became more frequent. Especially the temperature drops on the shoulder coolers increased, which led in March 2016 to depressurization of the casing at the junction of tuyere zone coolers and shoulders, and through the resulting burnout, red-hot charge materials were ejected onto the operating platform of the tuyere zone [1].

At the aforementioned conference of blast furnaces, Danieli Corus specialists explained the reasons for the high temperature drop across shoulder coolers by the development of the peripheral gas flow in the blast furnace hearth during the transition to PCI technology, i.e., allegedly by lowering the "cohesion" zone (the zone of the softened state of iron ore materials) almost to the level of near-tuyere foci and by breakthrough of the gas flow through this zone to the shoulder walls. They even illustrated the mechanism of this phenomenon with a series of figures [1]. However, this explanation is clearly wrong. In fact, when switching to PCI, the cohesion zone as a whole must not fall since the specific heat capacity of the gas flow practically does not change in this case while the specific heat capacity of the charge flow decreases due to a decrease in coke consumption. It should be stated that the erroneous interpretation of gas-dynamic processes in the DP-9 hearth formed incorrect recommendations and still does not allow fully mastering PCI technology at this furnace, where the record short-term

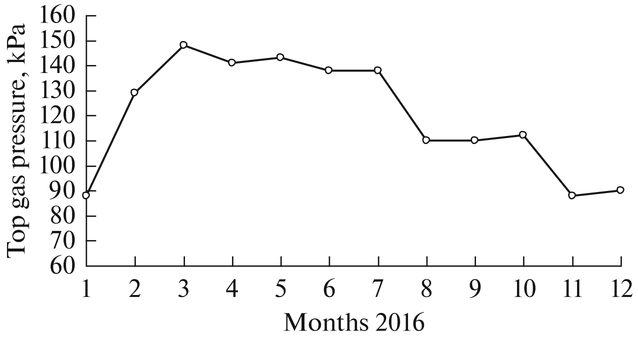


Fig. 1. Change in excess pressure of the top gas at the 5000-m^3 furnace by months in 2016.

achieved PCI consumption level is still 110 kg/t of cast iron.

The true reasons for the peripheral gas flow, the constant burning of the refrigerators of the furnace cooling system, and the failure of tuyeres throughout the entire period of DP-9 operation from the moment PCI began are determined by the changing conditions of occurring mechanical, gas-dynamic, and thermotechnical processes in the combustion zones.

The loosened zone (circulation zone) formed in front of the tuyere in the coke packing under the effect of the total mechanical energy of the blast flow decisively affects gas flow movement in the near-tuyere region. This energy determines the shape and area of the pseudo-stable vault above the loosened cavity and is basically the expansion energy (pressure energy). The kinetic energy of the blast blowing is 4–7% of the total mechanical energy of the blast blowing and has little effect on the size of the loosened zone. However, due to its directionality and the presence of a loosened zone, it is the next most important factor after the blast pressure energy in changing the circulation zone length. In this case, an increase in kinetic energy contributes to the elongation of the combustion zone only when the total mechanical energy of blast blowing does not decrease. If, at an increase in kinetic energy due to a decrease in the diameter of tuyeres, the blast consumption decreases and the total mechanical energy of the blast flow decreases due to a decrease in the energy of the blast pressure, the size of the combustion zones decreases. This promotes the development of a peripheral gas flow in the hearth, leading to the combustion of refrigerators in the shoulders [5, 6].

The main factor in ensuring the movement of the gas flow to the center of the lower zone of the furnace when controlled “from below” is the total mechanical energy of the furnace gas flow. It is responsible for the depth of gas penetration to the center of the hearth and maintaining temperatures, at which the smelting products remain in a liquid mobile state and there are no toterman formation conditions [5–7].

An important factor affecting the gas movement to the furnace center is the presence of a coke vent in the axial zone of the charge column, which is formed during control “from above.” Due to the high gas permeability of the vent, a significant fraction of the energy of the blast pressure is spent on advancing the gas to the center [8].

There is another powerful energy potential, which ensures the pushing of furnace gas, including towards the furnace center, but which was ignored until now. This is the energy of gas compression during its sharp cooling outside the loosened zone due to the intense development of reactions of coke carbon with CO_2 and H_2O of the gas leaving the loosened zone. Sounding of the hearth of blast furnaces shows a decrease in pressure towards the hearth center following a decrease in temperature, which also promotes the movement of the gas flow towards the center.

The inevitable significant change in the shape of the pseudo-stable vault above the loosened zone during PCI blowing also decisively affects the gas movement from the near-tuyere source to the inclined walls of the shoulders. This factor was also not yet noted in the literature. Coke combustion in the loosened zone is relatively slow due to the extremely limited reaction surface. Coke combustion is intensified only at the boundary of the loosened zone in a dense coke layer, where oxygen residues quickly disappear from the gas phase. In this case, the gas expansion due to combustion occurs relatively uniformly along the combustion zone length. The injection of natural gas, if any, only slows down the coke combustion and the heating of the gas near the blast furnace tuyeres. On the contrary, during PCI, a powerful source of gas expansion appears near the tuyeres due to intense concentrated combustion of coal dust. Above this zone of intense combustion of pulverized coal, the pseudo-stable coke roof must necessarily extend upward, increasing here the circulating movement of the hearth gas, which in this case can be partially directed to the walls of the shoulders and disable refrigerators of the blast furnace cooling system [4].

An attempt to restrict the gas flow to the periphery by increasing the kinetic energy of the blast at DP-9 was performed by reducing the tuyere diameter from 150 to 140 mm while reducing the excess pressure of gas down to 90 kPa (Fig. 1). This had the opposite effect of what was expected. It is the kinetic energy of the blast jet that initiates the vortex gas movement in the upper zone of the near-tuyere source, and it intensified. Besides, excessive kinetic energy of the blast turned the near-tuyere center into a kind of “coke-crusher” and strongly densified the dead-end wall of the loosened cavity. This promoted an even greater throwing of the gas flow back to the walls of the blast furnace shoulders [9, 10].

For further consideration of the results of the furnace operation at a decrease in the diameter of the

Fig. 2. Change in the blast consumption at the 5000-m^3 furnace by months in 2016.

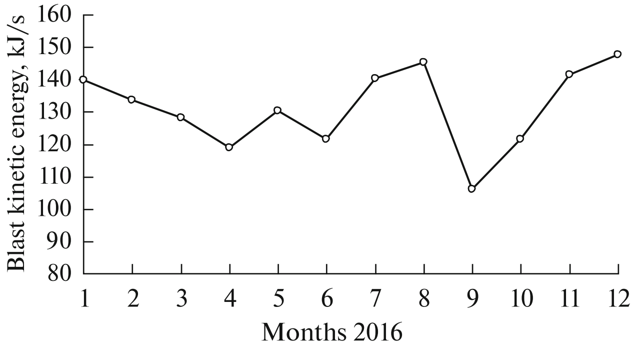


Fig. 3. Change in the blast kinetic energy at the 5000-m^3 furnace by months in 2016.

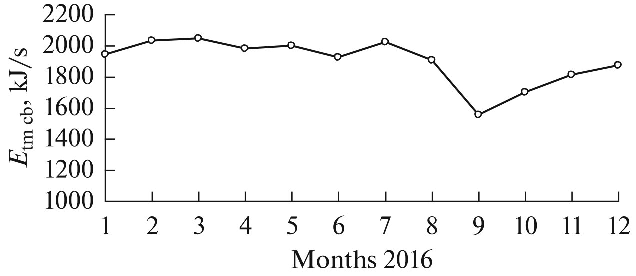


Fig. 4. Change in the total mechanical energy of the combined blast flow at the 5000-m^3 furnace by months in 2016.

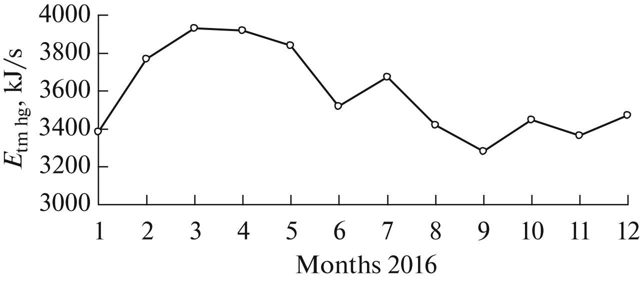


Fig. 5. Change in the total mechanical energy of the hearth gas flow at the 5000-m^3 furnace by months in 2016.

tuyeres and the determination of rational energy parameters of the blast and hearth gas, it is necessary to refer to the experience of the operation of this furnace that was described in [11], where monthly periods of its operation since 2000 were analyzed.

In October 2006 (the best period of DP-9 operation), productivity was 9826 t/day, specific coke consumption was 426.8 kg/t, blast consumption was 7812 m^3/min, blast pressure was 437 kPa, blast temperature was 1090°C, natural gas consumption was 87.1 m^3/t, oxygen concentration in the blast was 30.5%, and the coke smelting rate was 839 kg/(m^3 day). High performance and the smooth operation of the blast furnace indicated good heating and normal gas distribution in the hearth. The design parameters that can be considered rational for a furnace of this volume: the total mechanical energy of the combined blast flow at the tuyere cut is 2034 kJ/s and the total mechanical energy of the furnace gas flow is 5114 kJ/s.

Information on the most severe accident at PD-9 in 2011, which was preceded by long-term operation of the blast furnace for organizational reasons with a blast rate of 4955 m^3/min and a coke smelting rate of only 407 kg/(m^3 day) is also given in [11]. In this case, the energy indicators of the gas-dynamic mode significantly decreased: the total mechanical energy of the combined blast flow was only 65.3% and of the furnace gas was 47.6% of the value of these indicators in the best period of furnace operation. As a result, a toterman was formed at the hearth center, and when the skull slid from the shoulders along the entire ring, all four entrances were sealed and all 42 tuyeres were filled with slag up to the air duct. It is unacceptable to reduce the energy parameters of blast and hearth gas to such a level for a 5000-m^3 furnace with a hearth diameter of 14.7 m. The blast furnace was fired up during that period with great difficulties after a long stay.

The change in the flow rate of the blast, its kinetic energy, the total mechanical energy of the combined blast flow at the tuyere cut, and the total mechanical energy of the hearth gas during 2016 is shown in Figs. 2–5. In August, the furnace was already running on all tuyeres of this diameter.

The table shows the technical and economic indicators of blast furnace smelting using a 5000-m^3 furnace in 2016 with a change in the diameter of the tuyeres, the furnace operated on 150-mm tuyeres in the base (B) period and on 140-mm tuyeres in the experimental (E) period. The table shows that, at a decrease in the diameter of the tuyeres, the furnace productivity decreased from 9340 to 7874 t/day. At an increase in PCI from 71.4 to 87.57 kg/t, specific coke consumption decreased from 451.7 to 422.74 kg/t of cast iron (by 28.96 kg/t). Fuel consumption in coke

Table 1. Technical and economic indicators of blast furnace smelting in a 5000-m^3 furnace with a change in the tuyere diameter from 150 to 140 mm

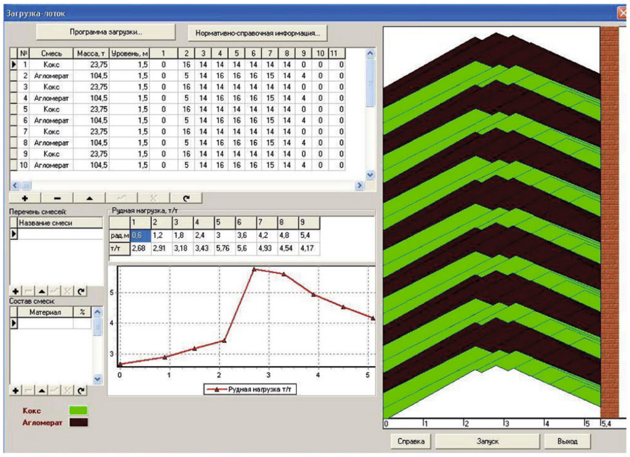
Indicators	Periods	
	B	E
Operation period, days	31	31
Tuyere diameter, mm	150	140
PCI consumption, kg/t	71.4	86.57
Productivity, t/day	9340	7874
Coke consumption, kg/t	451.7	422.7
Coke combustion rate, kg/(m^3 day)	843.8	665.7
Fuel consumption in coke equivalent, kg/t	519.0	505.3
Natural gas consumption, m^3/t	11.0	12.7
Blowing:		
flow rate, m^3/min	7953	7048
temperature, °C	990	1050
blast pressure, kPa (exc);	328	299
Oxygen content in blast, %	24.3	22.7
Top gas:		
blast pressure, kPa (exc)	148	110
temperature, °C	120	170
content, %:		
CO	24.1	21.7
CO_2	20.7	19.9
H_2	4.5	3.5
Current downtime, %	9.55	3.25
Quiet running, %	0.08	0
Flue dust removal, kg/t	11.2	20.8
Including trapped dust, kg/t	4.7	12.0
Slag yield, kg/t	429.7	448.0
Consumption factors, kg/t:		
ore	6.7	11.2
agglomerate AC no. 1	51.6	30.1
agglomerate AC no. 2	1331.0	1290.7
SevGOK pellets	259.0	349.9
Cast iron analysis, %:		
Si	0.63	0.85
Mn	0.19	0.17
S	0.012	0.011
P	0.087	0.084
Coke quality, %:		
moisture	3.6	2.7
ash	10.4	10.2
sulfur	0.5	0.5
M_{25}	88.2	88.2
M_{10}	6.6	6.5
+80 mm	6.6	6.1
–25 mm	3.4	3.4
CSR	59.9	60.7
CRI	29.6	30.4
Blast kinetic energy, kJ/s	128.2	145.4
Total mechanical energy of the blast flow at the tuyere cut, kJ/s	2043.6	1906.5
Total mechanical energy of hearth gas, kJ/s	3930.1	3420.5
Furnace gas output, m^3/s	177.78	157.27
Theoretical temperature of fuel combustion, °C	2181.1	2125.8

equivalent decreased by 13.7 kg/t: from 519.0 to 505.3 kg/t of cast iron. Here, attention is drawn to the decrease in the blast flow rate from 7953 m^3/min when the blast furnace operated on 150-mm tuyeres to 7048 m^3/min when using 140-mm tuyeres. The kinetic energy of the blast flow increased from 128.2 to 145.4 kJ/s at a decrease in the tuyere diameter, but this did not eliminate the peripheral gas flow in the hearth. This is explained by the fact that the total mechanical energy of the combined blast flow at the tuyere cut decreased by 6.3% (from 2043.6 to 1906.5 kJ/s) [5, 7].

The total mechanical energy of the furnace gas flow on tuyeres with a diameter of 150 mm was lower than its value in the best period of the blast furnace operation (5114 kJ/s) by 23.2%, i.e., only 3930.1 kJ/s. When switching to operation of a blast furnace with tuyeres with a diameter of 140 mm, the total mechanical energy of the hearth gas, which is responsible for the depth of gas penetration to the hearth center [7], decreased even more, to 3420.5 kJ/s, which is by 33.1% less than the rational value of this energy of 5114 kJ/s. The unfavorable reduction in both types of total mechanical energy explains the reason for the increase in the peripheral gas flow at a decrease in the tuyere diameter.

Further operation of DP-9 from 2017 to the end of 2019 was accompanied by an even more significant reduction in blast consumption. For example, the blast consumption in the furnace during that period was in the range of 4375–6658 m^3/min, which is unacceptable for a furnace with a hearth diameter of 14700 mm. In February 2018, another major overhaul was carried out with the replacement of a part of the furnace casing and refrigerators, as well as shotcreting of the lining from the shaft to the hearth. In April 2019, the blast furnace was again shut down for major overhauls to restore the lining from the shaft to the tap holes with the release of lower lining cast iron. However, after blowing, refrigerators and tuyeres in the furnace continued to fail, the skull did not hold on to the shoulders (the report of AMKR specialists at the XXIX Scientific and Technical Conference on Sintering Production "Improving the Quality of Prepared Iron Ore Raw Materials for Blast Furnace Production in Ukraine" (Krivoy Rog, AMKR, October 16–18, 2019). This was a consequence of the blast flow rate underestimated due to technological problems and an insufficient level of energy parameters of blast and furnace gas.

Gas-dynamic problems and the reasons for the peripheral gas flow after the introduction of PCI technology at DP-9 were also the result of an unsuccessful distribution of charge materials on the top when controlling the gas melting dynamics from above [1]. Estimating the value of individual controllable parameters of blast furnace smelting in the interrelated selection of optimal loading and blast modes, it should be recognized that coordinated control of blast-furnace smelting by control measures both from above and from below is required for normalization of the radial distribution of the gas flow [8]. The distribution of charge materials on the top largely determines, on the one hand, the degree of gas utilization and the specific coke consumption and, on the other hand, the gas permeability of the charge column and the possibility of intensifying blast-furnace smelting.



№	Смесь	Масса, т	Уровень, м	1	2	3	4	5	6	7	8	9	10	11
1	Кокс	23,75	1,5	0	16	14	14	14	14	14	14	0	0	0
2	Агломерат	104,5	1,5	0	5	14	16	16	16	15	14	4	0	0
3	Кокс	23,75	1,5	0	16	14	14	14	14	14	14	0	0	0
4	Агломерат	104,5	1,5	0	5	14	16	16	16	15	14	4	0	0
5	Кокс	23,75	1,5	0	16	14	14	14	14	14	14	0	0	0
6	Агломерат	104,5	1,5	0	5	14	16	16	16	15	14	4	0	0
7	Кокс	23,75	1,5	0	16	14	14	14	14	14	14	0	0	0
8	Агломерат	104,5	1,5	0	5	14	16	16	16	15	14	4	0	0
9	Кокс	23,75	1,5	0	16	14	14	14	14	14	14	0	0	0
10	Агломерат	104,5	1,5	0	5	14	16	16	16	15	14	4	0	0

Рудная нагрузка, т/т

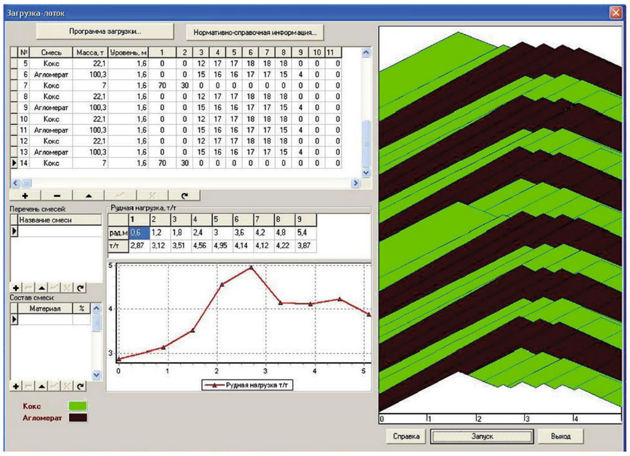
	1	2	3	4	5	6	7	8	9
рад.м	0,6	1,2	1,8	2,4	3	3,6	4,2	4,8	5,4
т/т	2,68	2,91	3,18	3,43	5,76	5,6	4,93	4,54	4,17

Название смеси

Материал	%

Fig. 6. Distribution of charge materials on DP-9.

From the beginning of 2017 to January 21, 2020, a typical two-batch charging cycle (Fig. 6), which is used in many European blast furnaces mainly to simplify the procedure for selecting acceptable loading modes and which does not take into account many differences in the operating conditions of DP-9 and European furnaces, was implemented at DP-9. In this loading mode, the ore load on the coke in the wide central vent increased by approximately unity [1]. At foreign blast furnaces, the intensity of the blast-smelting mode is usually higher and the hearth diameter is smaller, so they do not need to form a clean coke vent in the axial zone to ensure smooth running of the furnace. At the loading mode set on the DP-9, the coke was not loaded into the axial zone (at the first tilt station) at all, which excluded even the theoretical possibility of forming a narrow coke vent. Since January 21, 2020, DP-9 technologists applied an improved seven-portion loading mode, which provides for the supply of an additional portion of coke to the furnace center at angular positions *1* and *2* of the BZU tray (Fig. 7). However, this load mode is also far from optimal. It does not provide the formation of a narrow coke vent and creates a concentrated ore ridge in the middle of the top radius, which reduces the degree of gas utilization in the furnace and increases the specific coke consumption. Optimization of the distribution of charge materials on the top requires adjusting both the loading cycle and the set tilt angles of the tray, especially in its first positions.



№	Смесь	Масса, т	Уровень, м	1	2	3	4	5	6	7	8	9	10	11
5	Кокс	22,1	1,6	0	0	12	17	17	18	18	18	0	0	0
6	Агломерат	100,3	1,6	0	0	15	16	16	17	17	15	4	0	0
7	Кокс	7	1,6	70	30	0	0	0	0	0	0	0	0	0
8	Кокс	22,1	1,6	0	0	12	17	17	18	18	18	0	0	0
9	Агломерат	100,3	1,6	0	0	15	16	16	17	17	15	4	0	0
10	Кокс	22,1	1,6	0	0	12	17	17	18	18	18	0	0	0
11	Агломерат	100,3	1,6	0	0	15	16	16	17	17	15	4	0	0
12	Кокс	22,1	1,6	0	0	12	17	17	18	18	18	0	0	0
13	Агломерат	100,3	1,6	0	0	15	16	16	17	17	15	4	0	0
14	Кокс	7	1,6	70	30	0	0	0	0	0	0	0	0	0

Рудная нагрузка, т/т

	1	2	3	4	5	6	7	8	9
рад.м	0,6	1,2	1,8	2,4	3	3,6	4,2	4,8	5,4
т/т	2,87	3,12	3,51	4,56	4,95	4,14	4,12	4,22	3,87

Fig. 7. Distribution of charge materials on DP-9 with a new loading mode.

An improvement of the loading mode using the LOADING dialogue system [12] while optimizing the blast parameters will undoubtedly normalize the gas-dynamic smelting mode at DP-9, eliminate the source of emergencies, increase PCI consumption to 150 kg/t of cast iron, significantly reduce the coke consumption, and increase the furnace productivity.

To normalize the gas flow in the lower part of the furnace, it is necessary to reduce the excessive kinetic energy of the blast and increase the total mechanical energies of the blast and furnace gas. The first step for this should be to increase the tuyere diameter from 140 to 150 mm, or better, to 165 mm. Next, it is necessary to optimize the blast parameters using, for example, the "DUT'E" dialogue system developed by the Krivoy Rog Metallurgical Institute employees and allowing reasonable choices of blast parameters while maintaining the values of the generalizing indicators of the blast mode at the optimum level [13, 14].

The performed analysis of the operation of a blast furnace with a useful volume of 5000 m^3 showed the need for continual monitoring and regulation of the energy parameters of the blast and furnace gas flows, especially when using PCI. At a blast furnace of this volume, the blast flow rate must not be reduced to less than 8300–8500 m^3/min. The total mechanical energy of the combined blast flow at the tuyere cut is advisable to maintain a level not lower than 2100–2600 kJ/s and the total mechanical energy of the furnace gas flow at a level not lower than 5100–5300 kJ/s. It is also necessary to form a narrow coke vent on the top of the blast furnace and to stretch the ore ridge as much as possible.

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