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STUDY OF HEAT LOSSES IN A BLAST FURNACE WITH THE INJECTION OF PULVERIZED-COAL FUEL INTO THE HEARTH

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Studies were made of the changes in heat loss that occur during the operation of a blast furnace with pulverized-coal fuel (PCF). It is shown that the use of PCF increases heat losses relative to the furnace's heating capacity. These losses increase from 1.15% without PCF use and an intact lining to 3.7% with maximal lining wear and the use of PCF at a rate of 187 kg/ton pig iron. Minus the chemical heat of the top gas, the heat losses incurred relative to the heating power of the furnace increase from 2.78 to 8.81%.
Keywords: *blast-furnace technology, pulverized-coal fuel, heat losses, radiation, convection.*

The productivity of blast furnaces is increased significantly (by up to 50%) by replacing expensive coke by pulverized-coal fuel (PCF) and simultaneously implementing other measures (preparation of the charge, increasing the blast temperature, and enriching the blast with oxygen).

The injection of PCF also intensifies thermal processes. The combustion of PCF – which has a specific surface 300–500 times greater than that of coke – is accompanied by the formation of a cloud of molten ash particles. This sharply (compared to the combustion of coke) intensifies radiative heat transfer in the tuyere hearth, which has a dual effect. On the one hand, it increases the degree of superheating of the smelting products, while on the other hand it increases heat flow and heat loss through the tuyeres and the walls next to them.

The increase in the productivity of blast furnaces (BFs) that are changed over to PCF-technology is accompanied by greater mechanical, abrasive, chemical, and thermal loading of the lining by the charge materials and the furnace gases. This leads to a decrease in the thickness of the refractory lining and reduces the durability of the slag crust. Both of these developments increase heat loss.

Method of Determining the Heat Flows. Heat flows directed along a normal to the lining of the walls of a blast furnace are essentially heat losses to the environment. Five different sections can be identified over the height of the furnace, and there are differences between the sections in regard to the method that is used to determine the heat flux.

Section 1 – the uncooled top part of the shaft. The lining of the wall consists of a layer of fireclay, a rammed layer made of a slag-asbestos mix, and a steel shell. Heat flux is determined from an equation that describes steady-state heat transfer [1, 2]:

$$Q = \frac{t_i - t_f}{1/\alpha + R_f + R_m + R_y} F_1, \text{ W},$$

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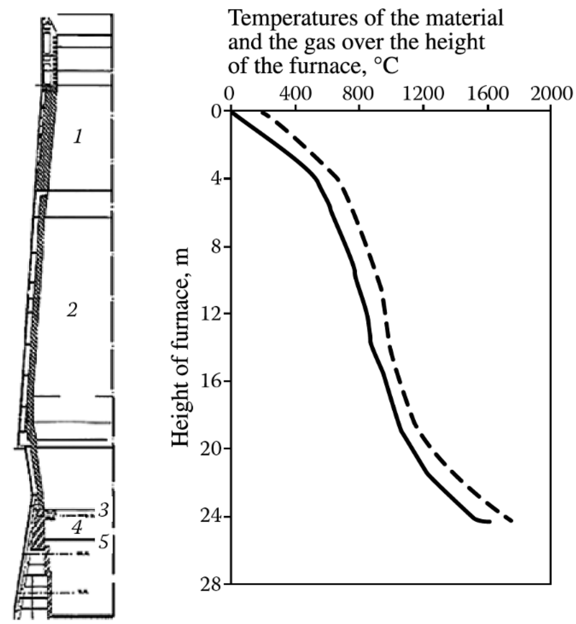

Fig. 1. Change in the temperature of the shaft (solid line) and gas (dashed line) over the height of the blast furnace.

where t_i is the temperature during the initial stage of heat transfer, this temperature being equal to the temperature of the charge at the gage level (see Fig. 1), °C; t_f is the temperature during the final stage of heat transfer, this temperature being equal to the temperature of the surrounding medium, °C; $1/\alpha$ is external heat resistance at the stage in which heat transfer, with the heat-transfer coefficient (α), takes place by free convection from the outside surface of the shell to the surrounding medium, $m^2 \cdot K/W$; $R = S/\lambda$ is internal heat resistance, $m^2 \cdot K/W$; λ is the thermal conductivity of a layer of the lining, W/(m·K); F_1 is the calculated area of the heat-transfer surface, which is assumed to be equal to the area of the outside surface of the shell over the height of section *1*, m^2; R_y is the heat resistance of the fireclay layer of the lining, this quantity depending on the degree of wear of the layer.

Section 2 – the cooled part of the shaft and the upper and lower parts of the bosh. In this study, we analyzed the heat losses for a cooling system composed of cooling panels that are installed flush against the shell. Each panel is nonuniform and includes a cast-iron base with fireclay-filled channels and a coil which is embedded in the panel to circulate coolant water. The inner part of the lining is made of fireclay. A slag crust may be formed on the surface of a panel if the lining has undergone a maximal amount of wear. Heat flux is determined from the equation that describes steady-state heat transfer [1–3] (here, heat flux is determined separately for the cooled part of the shaft and the upper and lower parts of the bosh):

$$Q = \frac{t_i - t_f}{R_y + R_{pn} + R_{slc}} F, \text{ W},$$

where t_i is the temperature during the initial stage of heat transfer, this temperature being equal to the temperature of the charge next to the inside surface of the wall at the gage level, °C; t_f is the temperature during the final stage of heat transfer, this temperature being equal to the temperature along the line on which the coils are installed inside the cooling panel; this temperature, determined by a method that was specially developed, does not differ substantially from the temperature of the coolant water, °C; $R_y = S_y/\lambda_y$ is the heat resistance of the fireclay layer of the lining and is determined in relation to the degree of wear of the layer; $R_{pn} = S_{pn}/\lambda_{pn}$ is the heat resistance of the panel; λ_{pn} is the average thermal conductivity of the panel, this quantity being determined by a specially developed method and depending on the percentages of the interior and surface of the panel that are occupied by the fireclay-filled channels, W/(m·K); $R_{slc} = S_{slc}/\lambda_{slc}$ is the heat resistance of the slag crust.

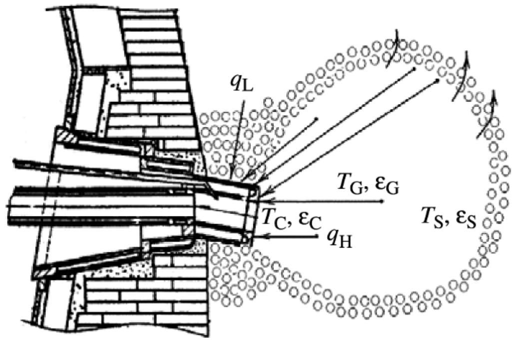

Fig. 2. Theoretical configuration of the tuyere zone.

The effect of PCF consumption on heat losses in sections *1* and *2* was taken into account in accordance with recommendations made by the company Danieli Corus BV (IJmuiden, the Netherlands)* on the basis of experimental studies that were made of the profile of these sections with the use of wear-measuring rods and thermocouples. Specialists with the company have concluded that the heat losses increase in proportion to the capacity of the furnace because of faster descent of the charge materials and the formation of irregular high-speed peripheral gas flows between the furnace wall and the charge.

Section 3 – the tuyere-zone hearth – is a cavity surrounded by red-hot coke and filled with circulating flows of the air blast, gaseous products of the combustion of coke and PCF, partially molten ash, and drops of the liquid smelting products. The end surface of each tuyere receives convective and radiative heat flows from the tuyere hearth; the lateral surface receives radiative heat flows directly from the red-hot coke and is also exposed to radiant heat flux from the part of the tuyere zone that is partially shielded by the coke. An estimate of the percentage of convective heat transfer which takes place showed that convection is of secondary importance in this case. Thus, below we present a method of calculating heat flux that occurs solely by radiation in accordance with the theoretical scheme that was chosen (see Fig. 2).

The radiant heat flux q_H reaching the copper (C – copper) end surface can be represented as the sum of the heat flux from the volume of gas in the tuyere zone (G – gas) q_{GC} and the inside surface (S – surface) of the cavity in the tuyere zone (TZ) q_{SC}:

$$q_H = q_{GC} + q_{SC},\ \mathrm{W/m^2}.$$

Radiant heat flux is determined in accordance with the Stefan–Boltzmann law [3, 4]:

$$q_{GC} = \varepsilon_{GC}\sigma_0(T_G^4 - T_C^4);$$

$$q_{SC} = \varepsilon_{SC}\sigma_0(T_S^4 - T_C^4),$$

where T_G, T_S, and T_C are the temperature of the gaseous volume in the TZ, the temperature at the surface of the TZ, and the temperature of the copper surface of the tuyeres, K; $\sigma_0 = 5.67\cdot10^{-6}$, W/(m^2·K) is the coefficient that describes the radiation of an absolute blackbody; ε_{GC} is the corrected emissivity of the gas–copper system; ε_{SC} is the corrected emissivity of the surface–copper system; ε_{GC} and ε_{SC} are found from the formulas obtained by Timofeev [4]:

$$\varepsilon_{GC} = \frac{\varepsilon_G\varepsilon_S(1+\varphi_{SC}(1-\varepsilon_G)(1-\varepsilon_G))}{B};$$

* Information from the technical proposal (Document No. P002646-TP, edition 1, from 12.18.2012) that the company Danieli Corus BV sent to the Alchevsk Metallurgical Combine for replacement of the lining of blast furnace No. 1 (with the use of an integrated design for the shell, the lining, and the cooling system developed by Hoogovens®). The replacement was planned for 2013/2014.

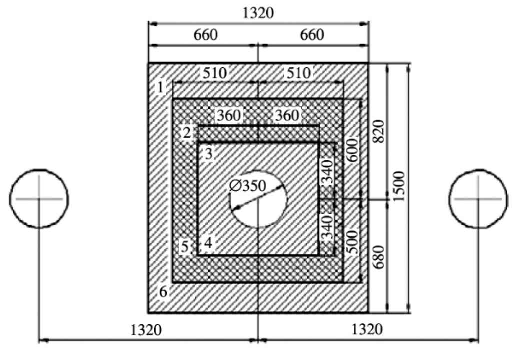

Fig. 3. Sections of the walls in the tuyere zones.

$$\varepsilon_{SC} = \frac{\varepsilon_S \varepsilon_C (1 - \varepsilon_G)}{B};$$

$$B = 1 - (1 - \varepsilon_G)(1 - \varepsilon_S)(\varphi_{SS} + \varphi_{SC}(1 - \varepsilon_G)(1 - \varepsilon_S)),$$

where φ_{SS} and φ_{SC} are the surface–surface and surface–copper slopes;

$$\varphi_{SC} = F_C/(F_C + F_S);$$

$$\varphi_{SS} = F_S/(F_C + F_S);$$

where F_C and F_S are the areas of the "copper surface" and the "TZ surface" (the former is determined from handbook data for oxidized copper); ε_S is "surface" emissivity (determined as the weighted-mean emissivity of the coke and the smelting products); ε_G is "gas" emissivity, i.e., the emissivity of the gas in the volume of the TZ cavity. This quantity is found by a specially developed method that was described in detail in [5].

The method is based on an approach proposed by Kutateladze and Borshchanskii in [6] for determining the absorption coefficient of a dust-bearing flow. Emissivity, which is equal to the absorption coefficient, is determined in relation to the concentration of particles of PCF ash after combustion.

Radiant heat flux on the lateral surface of each tuyere q_L is determined as the sum of the heat flux from the red-hot coke (K – coke) q_{KC} and the heat flux from the coke-shielded volume of gas in the TZ q_{GC}:

$$q_L = q_{KC} + q_{GC}, \ \text{W/m}^2;$$

$$q_{KC} = \varepsilon_{KC}\sigma_0(T_K^4 - T_C^4);$$

$$q_{GC} = \varepsilon_{GC}\sigma_0(T_G^4 - T_C^4).$$

The reduced emissivity of the coke–copper system is the same for all values of PCF consumption and is equal to $\varepsilon_{KC} = \varepsilon_K\varepsilon_C$ [3, 4]; the reduced emissivity of the gas–shield–copper system is equal to $\varepsilon_{GC} = \varepsilon_{KC}^{end}\beta_{shd}$, where β_{shd} represents the part of the volume of gas in the TZ that reaches the lateral surface of the tuyere through the layer of coke.

Section 4 – the walls in the tuyere zone (Fig. 3) – is comprised of the wall regions that are next to the tuyeres. The height of these regions is 1.5 m and their width is equal to the distance between the tuyeres. One distinctive feature of section *4* is the substantial effect of the cooled embrasures on the heat losses. We divided this section into different levels to

TABLE 1. Heat Losses in the Uncooled Part of the Shaft

Lining wear, %	Indices	PCF consumption, kg/ton pig iron		
		0	142	187
0	q_{av}, kW/m^2	0.243	0.282	0.330
	Q, MW	0.035	0.040	0.046
50	q_{av}, kW/m^2	0.276	0.320	0.375
	Q, MW	0.039	0.045	0.053

TABLE 2. Heat Losses on the Cooled Sections with a PCF Consumption of 0 kg/m^3

Section	h, m	F, m^2	t_y, °C	0% wear		100% wear, slag crust		100% wear, no slag crust	
				q, kW/m^2	Q, MW	q, kW/m^2	Q, MW	q, kW/m^2	Q, MW
Shaft			710	0.3		4.0		5.4	
	10.0	312			0.56		2.34		2.99
			1040	3.3		11.0		13.7	
Upper part of bosh	1.3	43			0.15		0.49		0.61
			1100	3.6		11.3		14.4	
Lower part of bosh	4.3	167			0.80		2.25		2.84
			1450	4.8		13.5		19.6	
Total					1.51		5.08		6.44

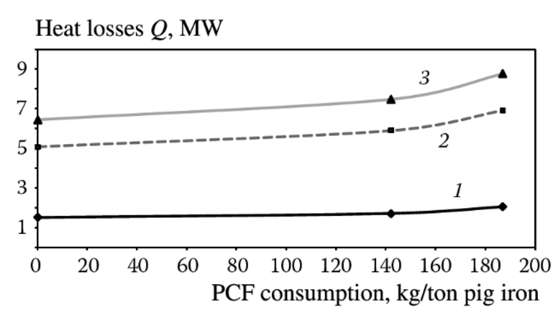

Fig. 4. Calculated heat losses in the cooled part of the furnace (section *2*) in relation to PCF consumption and the degree of wear of the lining: *1*) 0% lining wear; *2*) 100% lining wear + a slag crust; *3*) 100% lining wear with no slag crust.

improve the accuracy of the calculations: levels 1 and 6, where the effect of the embrasures is negligible; levels 2 and 5, where the effect of the embrasures is substantial; levels 3 and 4, where the effect of the embrasures is greatest. In calculating the heat flows, it was assumed that the walls are in direct contact with the incandescent coke and that the radiation from the volume of gas in the tuyere zone is almost completely shielded by the layer of coke.

TABLE 3. Heat Losses at the Tuyeres

Index		PCF consumption, kg/ton pig iron		
		0	142	187
Emissivity of the TZ	ε_G	0.02	0.41	0.69
	ε_S	0.47	0.46	0.56
End surface $F_E = 0.102\ m^2$				
Corrected emissivities	ε_{GC}	0.01	0.36	0.50
	ε_{SC}	0.52	0.21	0.08
Heat flux, kW/m^2	ε_{GC}	18.2	545	757
	ε_{SC}	291.3	118	47.5
$q_H = q_{KC} + q_{GC}$		309.5	669.0	804.5
Power associated with heat losses Q, MW	1 tuyere	0.034	0.070	0.08
	20 tuyeres	0.680	1.404	1.692
Lateral surface $F_L = 0.89\ m^2$				
Corrected emissivities	ε_{GC}	0.23	0.23	0.23
	ε_{SC}	0.0024	0.0720	0.1001
Heat flux, kW/m^2	ε_{GC}	130	130	130
	ε_{SC}	3.6	109	151
$q_L = q_{KC} + q_{GC}$		133.6	239	181
Power associated with heat losses Q, MW	1 tuyere	0.118	0.212	0.250
	20 tuyeres	2.38	4.24	5.00
Total heat losses, MW		3.05	5.64	6.69

Heat flux for section *4* is determined as the heat that is transferred from the coke layer through the layer of the refractory lining and on to a cooling element [3, 4]:

$$q = t_i - t_f/(1/\alpha + R_y),\ \ \text{W/m}^2,$$

where t_i is the temperature at the initial stage of heat transfer, taken equal to the temperature of the red-hot coke, °C; t_f is the temperature at the final stage of heat transfer, taken equal to the temperature of the cooled element, °C; $1/\alpha$ is the external heat resistance to heat transfer from the coke to the surface of the lining, this quantity being taken equal to zero because the temperatures of the coke and the surface of the wall are nearly equal; $R_y = S_y/\lambda_y$ is the heat resistance of the layer of the refractory lining (fireclay), m^2·K/W; S_y is thickness of the layer of fireclay at the gage level, taken as being equal to the shortest distance from that level to the cooling element (cooling slab, embrasure).

Analysis of the Results. The heat flows were calculated for a 1501-m^3 furnace for different degrees of wear of the lining (03, 30, 50, and 100%) and different values of PCF consumption (0, 142, and 187 kg/ton pig iron).

The intensity of the heat flows (and the heat losses) is characterized by the heat flux q, W/m^2. The power associated with the heat flows (and heat losses) is determined from the formula

$$Q = qF,\ \ \text{W, kW, MW},$$

where F is the area of the heat-transfer surface, m^2.

TABLE 4. Heat Flows to the Walls in the Tuyere Zone

Index	PCF consumption, kg/ton pig iron					
	0		142		187	
	q, kW/m^2	*Q*, kW	*q*, kW/m^2	*Q*, kW	*q*, kW/m^2	*Q*, kW
Fireclay lining not worn						
Level 1	3.26	1.53	3.78	1.79	4.44	2.08
Level 2	5.55	1.83	6.44	2.12	7.55	2.49
Level 3 + 4	11.70	4.60	13.57	5.34	15.91	6.26
Level 5	4.90	1.30	5.68	1.51	6.66	1.76
Level 6	2.25	0.81	2.61	0.94	3.06	1.10
Total, kW, for 1 TZ		10.07		11.69		13.69
Total, kW, for 20 TZs		201		234		274
Lining is worn 30%, parts of the steel embrasure and the copper tuyere are exposed						
Level 1	4.24	1.99	4.91	2.31	5.77	2.71
Level 2	7.21	2.74	8.37	3.18	9.81	3.73
Level 3 + 4	118	46.5	212	83.5	250	98.5
Level 5	6.31	1.67	7.38	1.96	8.59	2.28
Level 6	2.92	1.05	3.39	1.22	3.98	1.44
Total, kW, for 1 TZ		53.95		92.19		108.7
Total, kW, for 20 TZs		1079		1844		2162

In the uncooled part of the shaft (section *1*), with the height $h = 5.0$ m and the surface area $F = 140$ m^2, the heat losses are relatively small when the temperature of the charge is within the range 470–710°C (Table 1).

In the cooled part of the shaft and the upper and lower parts of the bosh (section *2*), the heat losses are proportional to the temperature of the charge (Table 2).

The heat losses for different values of PCF consumption were assumed to be proportional to the increase in the productivity of the furnace:

PCF consumption, kg/ton pig iron	0	142	187
Productivity, %	100	116	136

It is apparent from the dependence of the heat losses on PCF consumption and the degree of lining wear (Fig. 4) that the losses are 4–5 times greater when the wear of the lining is greatest. The values calculated for heat loss should be used in the design of future cooling systems.

In the tuyere zone (section *3*), the heat losses at the tuyeres are determined mainly by radiation from the gaseous volume. The calculated results shown below were obtained for the following conditions: temperature of the gaseous volume $t_G = 2000$°C; temperature of the coke surrounding the surface of the TZ, $t_S = 1500$°C; temperature of the copper surface $t_C = 30$°C. Table 3 shows the values of heat flux calculated for the tuyeres. Radiative heat flux from the gaseous volume increases with an increase in PCF consumption as a result of an increase in emissivity; at the same time, radiation from the inside surface of the TZ decreases because the diathermicity of the TZ decreases as its emissivity increases. The use of PCF sharply increases total heat losses at the tuyeres, the losses here increasing by a factor in the range 2–2.5.

TABLE 5. Total Heat Losses with 100% of the Lining Present, 50% of the Lining Worn, and All of the Lining Worn in the Presence of a Slag Crust (heating capacity of the furnace Q_{tot} = 450 MW, heating capacity without top gas Q_{WTG} = 188 MW)

Index	PCF consumption kg/ton pig iron		
	0	142	187
Losses on different sections of the furnace, kW (%), with 100% of the lining in place			
Uncooled part of the shaft	35(100)	40(116)	48(136)
Cooled part of the shaft	881(100)	1021(116)	1198(136)
Upper part of the bosh	187(100)	216(116)	254(136)
Lower part of the bosh	776(100)	900(116)	1055(136)
Walls of the TZ	201(100)	234(116)	274(136)
Tuyeres	3042(100)	5644(185)	6692(219)
Bottom of the hearth	93(100)	108(116)	124(136)
Total, kW	5216(100)	8163(156)	9644(184)
As a % of Q_{tot}	1.15	1.82	2.14
As a % of Q_{WTG}	2.78	4.35	5.13
Losses on different sections of the furnace, kW (%), with 50% wear of lining			
Uncooled part of the shaft	40(115)	46(131)	52(148)
Cooled part of the shaft	1282(145)	1487(168)	1643(186)
Upper part of the bosh	296(158)	343(183)	402(214)
Lower part of the bosh	1208(155)	1401(180)	1642(211)
Walls of the TZ (30%)	1679(895)	1844(917)	2162(1075)
Tuyeres	5644(185)	6692(219)	
Bottom of the hearth	133(143)	154(165)	181(194)
Total, kW	7080(135)	10919(209)	12774(244)
As a % of Q_{tot}	1.57	2.43	2.83
As a % of Q_{WTG}	3.77	5.81	6.79
Losses on different sections of the furnace, kW (%), with maximum lining wear + a slag crust			
Uncooled part of the shaft (50%)	40(115)	46(131)	52(148)
Cooled part of the shaft	2773(314)	3217(365)	3771(428)
Upper part of the bosh	578(309)	670(358)	786(420)
Lower part of the bosh	2149(276)	2493(321)	2923(376)
Walls of the TZ (30%)	1679(895)	1844(917)	2162(1075)
Tuyeres	3042(100)	5644(185)	6692(219)
Bottom of the hearth	133(143)	154(165)	181(194)
Total, kW	9794(187)	14068(269)	16567(317)
As a % of Q_{tot}	2.17	3.13	3.68
As a % of Q_{WTG}	5.21	7.48	8.81

Calculations of the heat flows to the walls in the TZ (Table 4) were performed for a completely intact lining and for a lining that had already worn 30%. In the latter case, it was assumed that part of the steel embrasure was exposed, and the heat flows were calculated by a method that made allowance for the projecting parts of the tuyeres. Also, the changes in the heat flows as a function of PCF consumption were assumed to be proportional to the change in the productivity of the furnace.

Table 5 shows data on the effect of PCF consumption on the heat losses for different amounts of lining wear. The largest losses are concentrated in the tuyere zone, which accounts for 62–72% of the heat lost by the furnace as a whole both when the lining is fully intact and when it has undergone the maximum amount of wear.

The heat losses seen in relation to the heating capacity of the furnace (the chemical heat generated by the coke and the PCF) increase from 1.15% with an unworn lining and no PCF use to 3.7% with maximal wear of the lining and the use of PCF at the rate 187 kg/ton pig iron. The heat losses referred to furnace heating capacity minus the chemical heat of the top gas increase from 2.78 to 8.81%.

Conclusions

1. The industrial use of PCF is accompanied by an increase in the amount of heat lost to the environment due to the intensified operation of the furnace. The injection of PCF into the tuyere zone sharply increases thermal radiation because of the formation of a luminous flame with a high emissivity. The result is overheating of the combustion products in the hearth, redistribution of temperature over the height of the furnace, and a significant increase in heat loss.

2. Calculations performed by the methods that have been developed showed that that in the presence of a fully intact lining furnace heat losses increase from 5.22 MW with a PCF consumption of 0 kg/ton pig iron to 8.17 MW and 9.63 MW with the consumption of PCF at rates of 142 and 187 kg/ton pig iron, respectively. The main heat losses are concentrated in the lower part of the furnace: 0.78, 0.90, and 1.06 MW in the bosh at PCF consumption values of 0, 142, and 187 kg/ton pig iron, respectively. The heat losses in the tuyere zone were 3.04, 5.64, and 6.69 MW at PCF consumption values of 0, 142, and 187 kg/ton pig iron, respectively.

3. Heat losses are significantly affected by the wear of the lining. In the case of a PCF consumption of 187 kg/ton and almost complete wear of the fireclay lining, the heat losses reach 16.6 MW – which is equivalent to 8.8% of the heating capacity of the furnace.

4. The method presented here together with the results from a study of heat losses can be used to design new cooling systems for blast furnaces.

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