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The Studies of Heat and Gas Dynamic Operation in the "Dry" Zone of Blast Furnace and Application of the Results

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Abstract

The results of the thermal and gas dynamic operation of "dry" zone of the blast furnace are given. The possibility of improving the furnace heat operation through a more efficient use of heat and reduction potentials of the gas flow, its distribution, taking into account the value of external heat losses, shaft profile and cooling, the properties of the charge materials and energy resources flow is shown.

Key words: *blast furnace, heat exchange, gas dynamics, heat losses, peripheral zone, scaffold, inversion, thermal boundary layer*

The processes of heat exchange and gas dynamics occurring in a shaft of the blast furnace (BF) and its peripheral zone determine the wear and profile of the shaft, the recovery operation of the gas flow and thermal preparation of charge materials before their entering into the lower high-temperature horizons of the furnace.

The scientific and methodological basis of the study of the development of heat-gas-dynamic processes in a "dry" zone of BF is the laws of gas dynamics and heat transfer, implemented in the mathematical model developed by V.K. Khrushch [1]. The analysis and forecast of blast furnace parameters was carried out using a thermal power model of I.D. Semikin [2]. To adapt and test the results of calculations in the real conditions of the furnace conditions there were performed temperature measurements of casing shell, thermal loads of water-cooled elements and blast furnaces in general during the period of their work, at the stops and during injection period. Subsequently, the staff of the Institute of Ferrous Metallurgy of National Academy of Sciences of Ukraine realized the control subsystem of external heat losses and coke consumption for their covering as a part of the automated technological process control system (APCS) of BF No. 9 of PJSC "ArcelorMittal Krivoy Rog" ("AMKR") (Fig. 1) [3]. The error of measurement of heat losses in the water cooling system in the BF was 5-21% at manual measurement and 4-5% in the automated mode.

Total heat losses of the cooling system and the coke consumption for their coverage are used to control the heat operation of the blast furnace. By increasing/decreasing the value of external heat losses and consumption of coke for their coverage the warning signal of heating/cooling, the "disorder" in the heat operation of the furnace is formed (Fig. 1).

To establish the nature of these changes in an automated mode there are controlled such heat and power characteristics as heat deficit, heat capacity and heat-availability factor (HAF). Heat deficit allows you to control the energy consumption for heating and intensity of the process, heat capacity allows to control the amount of heat supplied to the furnace and production expansion, HAF gives the nature of the distribution and usage of fuel heat.

The alarm signal about the the increase (decrease) of external heat losses per 1 MW during the hour is implemented in the subsystem on the main video frame **«Внешние Q»** («External Qs») **by a warning sign** (see Figure 1).

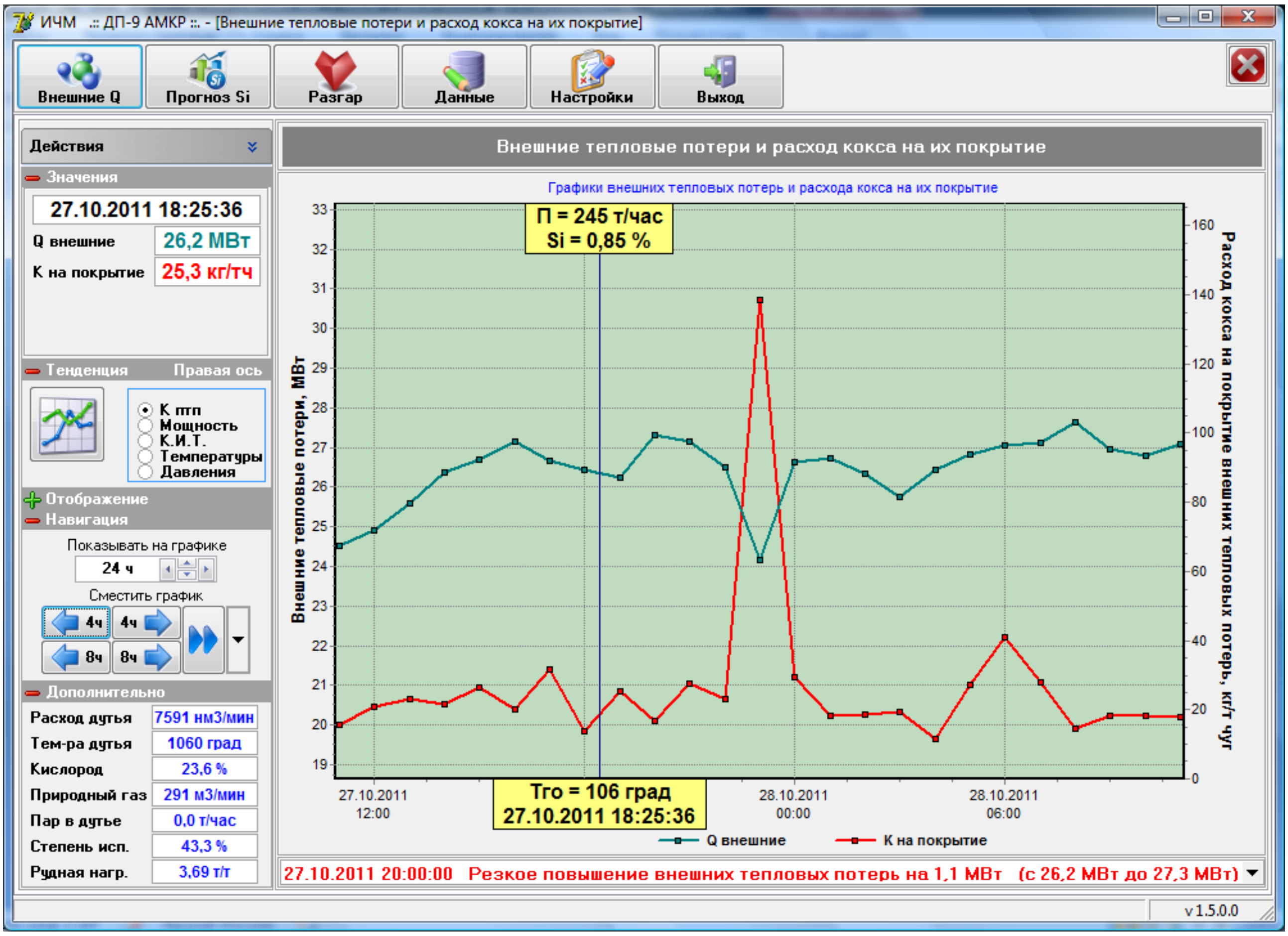
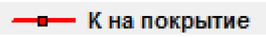


Figure 1 The video frame of the measurement of external heat losses (

) and control of coke consumption for their coverage (

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Coke consumption for coverage of external thermal losses is 10-50 kg/t of pig iron or 2-10% of the total consumption of coke [2]. In the furnace shaft external thermal losses are 20-50% of their total amount BF. The quantity of external heat losses in the furnace shaft is determined by the development of heat exchange processes in countercurrent of gas and charging materials in the “dry” zone of the shaft with regard to its design and operating parameters of the cooling system, gas flow, its distribution and charge material properties [1, 2].

With the use of heat-gas-dynamic model of “dry" zone of the furnace, the calculations were made, which then were compared to the results of experimental and theoretical studies [2, 4, 5] and showed good correspondence.

The results of the research allowed specifying and quantifying the impact of the development of the processes of heat transfer and gas dynamics in the shaft for heat gas-dynamic parameters of the BF operation taking into account the consumption and temperature of shaft gas, blast furnace gas pressure, porosity and size of pieces of the charge (Table 1).

Table 1 The influence of gas flow parameters and properties of the charge materials on thermal gas-dynamic parameters (+ increase, - decrease)

No.	Factors	Thermal losses in the shaft/ charge temperature in the shaft, %	Upper pressure fall/ pressure fall in the shaft, %		Gas temperature in the shaft/on the furnace top,%	Gas speed in the shaft/on the furnace top,%
1	Decrease of shaft gas consumption from 100% to:					
1a	10 %	-19/-20	-32/-24		-19/-32	-20/-28
1b	20 %	-56/-58	-66/-53		-57/-63	-50/-51
1c	40 %	-80/-79	-84/-79		-78/-66	-72/-64
2	Increase of blast furnace gas pressure from $0.5 \cdot 10^5$ Pa to:					
2a	$0.5 \cdot 10^5$ Pa	+2/+3	-36/-32;	-23[1]/-	+1/-1	-15/-26
2b	$1.0 \cdot 10^5$ Pa	+3/+5	-54/-50	-37[1]/-	+2/-2	-28/-41
2c	$1.5 \cdot 10^5$ Pa	+4/+6	-64/-61	-47[1]/-43[1]	+3/-3	-39/-51
3	Increase of shaft gas temperature of 900 °C by:					
3a	100 °C	+12/+10	+6/+5		+11/+10	+6/+5
4	Increase of charge average porosity of 0.2 m^3/m^3 by:					
4a	0.1 m^3/m^3	-3/-4	-60/-58		-3/+2	-4/-32
4b	0.2 m^3/m^3	-8/-9	-82/-80		-6/+4	-14/-49
4c	0.3 m^3/m^3	-14/-15	-92/-90		-9/+7	-26/-58
4d	0.5 m^3/m^3	-31/-28	-98/-98		-13/+21	-44/-68
5	Increase of average size of charge of 5 mm by:					
5a	5 mm	-0,4/-3	-26/-22		-2/+3	+5/+2
5b	25 mm	-8/-16	-70/-66		-10/+10	+11/+6
5c	45 mm	-15/-24	-82/-78		-13/+18	+13/+12
5d	75 mm	-24/-33	-88/-86		-14/+31	+14/+20

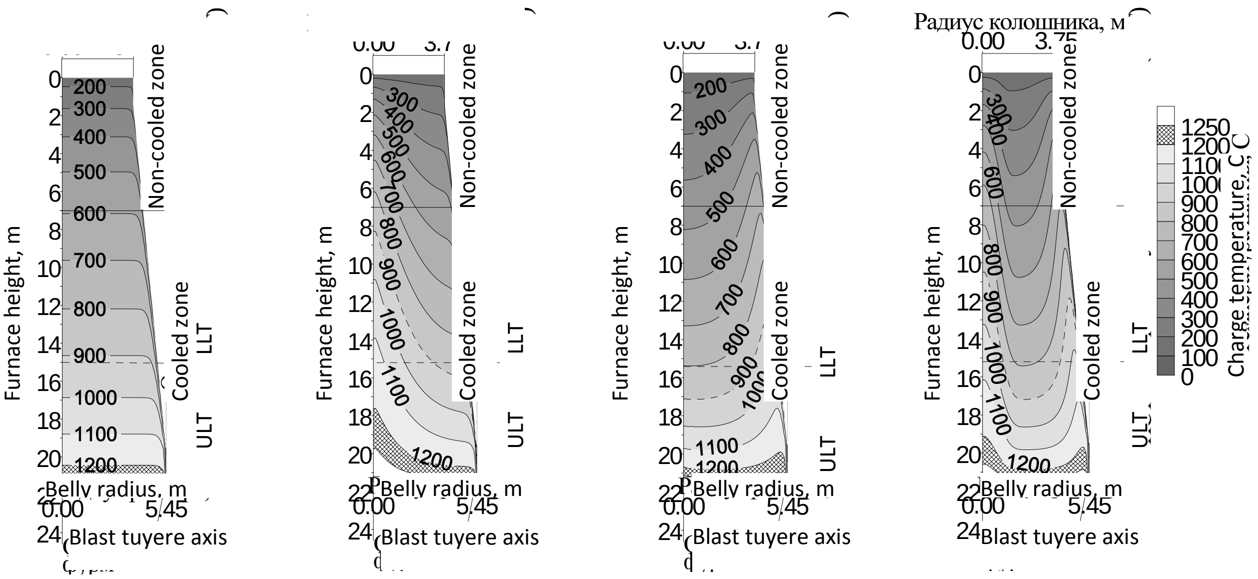
1 – according to the data of A.A. Tomash [5]

Reduction of shaft gas consumption at other equal conditions reduces heat amount for heating of the charge, therefore decreasing the temperature of the charge and the gas, the gas flow rate and pressure falls (Table 1). Increase of the temperature of shaft gas increases the amount of heat entering the “dry" zone. This causes an increase of temperature, heat losses and losses of volume of gas, which results in an increase in gas flow rate and pressure falls (Table 1).

The increase in the porosity of the charge at other equal conditions leads to an increase in the proportion of free space for gas in the furnace, causing reduced gas speed and pressure drop. This causes the gas to give less heat to the charge, so the heating of the charge is reduced, and the loss of heat with outgoing blast furnace gas increases (Table 1). The increase on charge average size at other equal conditions, including maintaining the porosity, reduces the contact area of gas with the charge, reducing the total volume of the heat transfer coefficient from gas to the charge, increasing the top gas temperature, reducing the pressure loss and increasing gas speed (Table 1).

The consumption of shaft gas for heating of the charge materials, pressure and gas flow rate has a greater impact than its temperature and the properties of the charge materials (Table 1). For application at SE PJSC “AMKR" the distribution of gas flow at maintaining the average gas permeability of the charge in the horizontal sections at other equal conditions effects on change of average temperature of gas and charge over the cross section or volume, pressure and speed of the gas at ~1-5%, external heat loss in the shaft at ~10-20%.

The results of the calculation of the temperature distribution of the charge in the BF shaftD, corresponding to a uniform, central, peripheral and actual gas distribution at other equal conditions, are shown in Figure 2. The boundary of the upper and lower levels of heat transfer (ULT and LLT), which corresponds to an average charge temperature of 900 °C, is shown in Fig. 2 by the dashed line. The isotherms marked in Figure 2 with shaded area show the boundary zone with temperatures of 1200-1250 °C.



a - even b – central c – peripheral d – actual

Figure 2 The distribution of the charge isotherms in the BF shaft with the capacity of 2000 m^3 at different gas distribution

The performed studies of the effect of gas distribution on the patterns of development of heat transfer processes in a "dry" zone of the shaft showed that the option of central gas distribution is more economically advantageous (Fig. 2b) due to the reduction of external heat loss, which is consistent with the findings obtained in the analysis of experimental studies of furnaces with central and peripheral gas distribution.

On the basis of performed calculations with the development of heat exchange processes in the peripheral zone of BF the temperature distribution of the charge from the stock line on different distances from the wall is obtained (Fig. 3a). It was found that there is an inversion of the temperature field below the cooled and non-cooled areas as an abrupt change in temperature indicated by circle A of curve 1 (Fig. 3a), the value of which depends on the parameters gas flow, its distribution, the properties of the charge materials, guard condition[1] [6], the presence of cooling plates brows and heat operation of the cooling system.

Temperature field inversion can be observed not only at the junction of cooled and non-cooled part of the shaft, but also in other areas where there is intense heat loss. For example, circles B and C of the curve 1 (Fig. 3a) indicate projections of cooling plates. The temperature distribution illustrated in Fig. 3a helps in melts adhesion and formation of accretion in the area of inversion of temperature field, especially in the border of the cooled and non-cooled areas, which was detected on the furnace the capacity of 2,000 m^3 during its stop and blowing up to 6-7 rows of shaft refrigerators. The mentioned accretion was predicted before the blowing in the study of the state of the guard of BF by thermographic method using manual measuring data of the shell temperature and and heat loss in the cooling system of the furnace (Fig. 3b).

[1] Blast furnace guard is a multi-layered wall consisting of the ledge, lining, refrigerator and furnace shell.

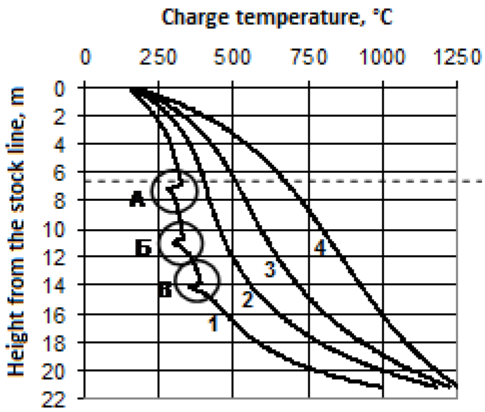


Figure 3 The charge temperature distribution by the shaft height (a) of BF with the capacity of 2,000 m^3 and its shell thermogram; (b) the distance from the wall in mrn.

The method of definition of boundaries of BF peripheral zone was suggested to determine the effect of cooling system of the temperature field in the furnace shaft, which is different and depends on the design parameters and the guard parameters, the cooling system operation and the thermal gas-dynamic mode of the furnace operation.

The boundaries of the peripheral zone in the BF shaft were determined using the theory of the thermal boundary layer [7]. The thickness of the thermal boundary layer in the furnace shaft is determined as a layer near the wall, wherein the gradient of temperature change along the furnace radius is $dT/dr > 0{,}01$, where T is the gas temperature, r is the radius of the furnace.

The results of calculation of the thermal gas-dynamic processes in the furnace shaft

showed that the cooling system has an effect on the heat transfer in the wall zone to the variable depth of about 200-700 mm. For the furnaces with the capacity of 2,000-5,000 m^3 it is ~ 3-10% from the furnace radius. The determining influence on the change of the thickness of the thermal boundary layer in the shaft and the temperature of the charge on its wall, the temperature of the surface of the shaft is made by lining thickness, flow rate and temperature of the shaft gas, porosity and size of pieces of the charge. The temperature and water flow in the cooling system has less impact on the change in the thickness of the thermal boundary layer in the furnace shaft.

Using the information about the size of the peripheral, intermediate and central zone, the volume of external heat loss and composition of the top gas the technical and economic parameters of these zones and the furnace in general were forecasted (Table 2).

Table 2 The parameters of thermal operation of BF No.9 by the zones and the furnace in general with 50% residual thickness of the lining

Parameters	Zones			
	peripheral	interme-diate	central	furnace in general
Zone size in the shaft by the radius, m	0.2 - 0.45	3.2 - 4.7	2 - 2.9	5.4 - 8.05
Thermal capacity of the furnace, MW	155	871	167	1193
Assimilated thermal capacity, MW	37	382	69	488
Idle power, MW	70	0	0	71
External heat losses, MW	30.7	0	0	30.7
Blast consumption by balance, m^3/min	852	4784	918	6554
Coke carbon HAF	0.478	0.478	0.457	0.475
Natural gas carbon HAF	0.157	0.157	0.118	0.151
HAF average value	0.439	0.439	0.415	0.435
Pig iron thermal deficite, MJ/t of pig iron	329	3369	611	4309
Expenditures per 1 t of pig iron:				
coke, kg/t	52	365	71	488
coke for coverage of heat losses, kg/t	20	0	0	20
natural gas, m^3/t	9	53	10	73
conditional fuel, kg/t	63	427	83	573
Productivity, t/hr	38.1	316.8	53.1	408.0
Level of direct reduction of iron (rd) according to Pavlov, %	1.8	33.8	47.8	32.7
CO usage degree, %	41.4	41.1	30.1	39.6
Tuyere zone theoretic temperature, °C	2110			

Dimensions of the central zone were defined using information about the actual distribution of the composition of blast furnace gas according to the data of radial gas sampling and temperature changes along the radius of the furnace top [8]. In the calculations there was made an assumption that the boundary of the central zone is the point at which the gradient of changes of radial gas composition is close to zero or changes the sign. This assumption allowed to estimate the average composition of the blast furnace gas in three zones of the furnace: central, intermediate and peripheral.

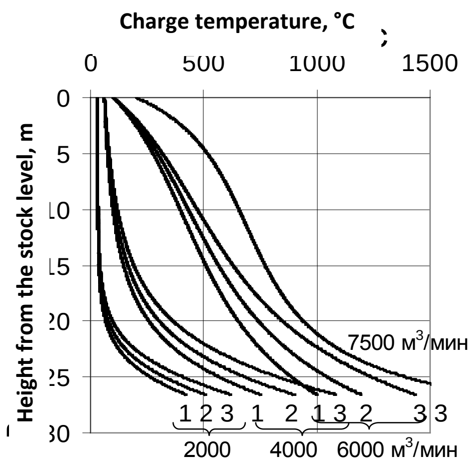


Figure 4 The dependence of charge material temperature during blowing on the consumption and blast temperature (1 – 100; 2 – 500; 3 – 1000 °C)

The results of thermal power calculation showed that the main part of furnace productivity (~80-90%) is determined by the thermal performance of the central and intermediate zone of the furnace, the rest ~10-20% is determined by peripheral zone. Thus, the consumption of coke on the coverage of external heat losses in the central and intermediate zones operating in an adiabatic mode is equal to zero, but in the peripheral zone it reaches 4-10% and more of specific coke consumption in the furnace in general and depends on the value of the external heat losses.

In the peripheral zone of the degree of direct iron reduction has low value because of the lack of heat and its consumption to cover the external heat losses. The sustainable management of thermal performance of the BF peripheral zone helps to reduce heat load in this area, which is a reserve for increasing the HAF, assimilated thermal capacity, the degree of direct iron reduction, and, consequently, the performance by 7-8%, and the reduction of the specific coke consumption by 4-5% for the whole furnace.

The proposed methods of calculation of heat and gas dynamic operation of the blast furnaces have been successfully tested for the verification and implementation of the thermal gas-dynamic mode of BF blasting with the capacity of 5,000 m^3 with the usage of heated … (Fig. 4) [9]. This technology effectively allows to heat the charge materials along the furnace height primarily due to increased consumption of the blast and secondarily by raising its temperature, as compared to existing technologies of BF blowing on atmospheric blast and combined one with natural gas (Fig. 4).

Conclusions

A method for predicting the flow of heat exchange processes between the gas flow and the charge in the "dry" and the peripheral zone of the furnace was developed and tested. This method allows to control the wear profile of the mine, to take evidence-based decisions to change the thermal gas dynamic mode of the furnace operation to match gas-dynamic and thermal operation of top and bottom of the BF, which is especially promising for the development of the blowing program.

The automated control system of external heat losses and consumption of coke for their coverage in BF can increase the efficiency of the real-time management of its thermal mode of operation, the stability of the quality of produced pig iron, the life of operation of lining and refrigerators of BF due to early detection and assessment of causes of deviation in thermal and gas-dynamic mode of furnace operation.

Using the theory of the thermal boundary layer there was developed a criterion and method for determining the boundaries of the peripheral zone; thus there was found that its thickness by the shaft height from the furnace ranges within 200-700 mm.

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