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ANALYSIS OF HEAT LOADS AND LINING WEAR OF BLAST-FURNACE CRUCIBLE OF VARIOUS DESIGNS

The article presents the results of analysis of thermal operation and hearth lining melting of blast furnaces of various designs on the basis of information from the system of monitoring of thermal operation and hearth lining melting – mathematical model "Hearth" developed in Iron and Steel Institute NAS of Ukraine (ISI NASU). Realization of continuous monitoring of the hearth melting in blast furnaces made it possible to estimate the effect of using "ceramic cup" in terms of the value of heat losses of the hearth and coke consumption for their compensation. It is established that the value of specific heat loss per unit volume of blast furnace in blast furnaces with a "ceramic cup" ~ 0,4-0,7 kW/m^3, in blast furnaces without it ~0,9-1,1 kW/m^3. Ceramic cup gives savings of about 1 kg/t-HM of coke.

Keywords: Blast furnace crucible; heat losses; lining wear

1. Introduction

The blast-furnace crucible is the area of the furnace whose lining experiences chemical, mechanical effects due to iron reduction and formation of final slag, high temperatures and movement of melts. It is the condition of the hearth and blast-furnace bottom lining that largely determines the duration of the blast furnace campaign. Therefore, increasing the durability and operational reliability of the hearth and blast-furnace bottom of modern blast furnaces is an important task.

The issues of improving the operational reliability of the hearth and prolonging the campaign of blast furnaces are solved by [1-3]:

- improvement of blast furnace hearth and hearth bottom designs, application of new refractory materials to ensure reliability of blast furnace operation;
- selection of a reliable system or improvement of the existing blast-furnace crucible cooling system;
- use of modern automated process control systems that include a subsystem for controlling the hearth lining.

The modern direction in the design of the blast-furnace crucible is based mainly on the following [1-3]:

- increase in the height of the hearth;
- increasing the height of the sump depth;
- reduction in the thickness of the hearth bottom;
- reduction in the thickness of the hearth walls;
- use of new generations of refractory materials for the blast-furnace crucible.

In the modern methodology of blast furnace hearth design, two main directions are being developed (Fig. 1) [4]:

- the "thermal" approach is an attempt to link the combination of refractory materials with the cooling system, using materials with high thermal conductivity based on graphite, semigraphite and carbon;
- the "ceramic" approach uses a combination of wear-resistant materials based on carbon and ceramics ("ceramic cup").

At the moment, the following basic methods of controlling the residual thickness of the lining are used in the world practice [5-8]:

1. core drilling;
2. calorimetric (determination of thermal loads of the blast-furnace crucible cooling system);
3. thermometric (determining the line temperature of the blast-furnace crucible);
4. ultrasonic (determining the time of passage and reflection of ultrasonic vibrations from the inner surface of the blast-furnace crucible line.

Other methods, such as the method of radioactive isotopes, the electrical method (based on breaking the electric circuit at the breakdown of the lining), the electromagnetic method and

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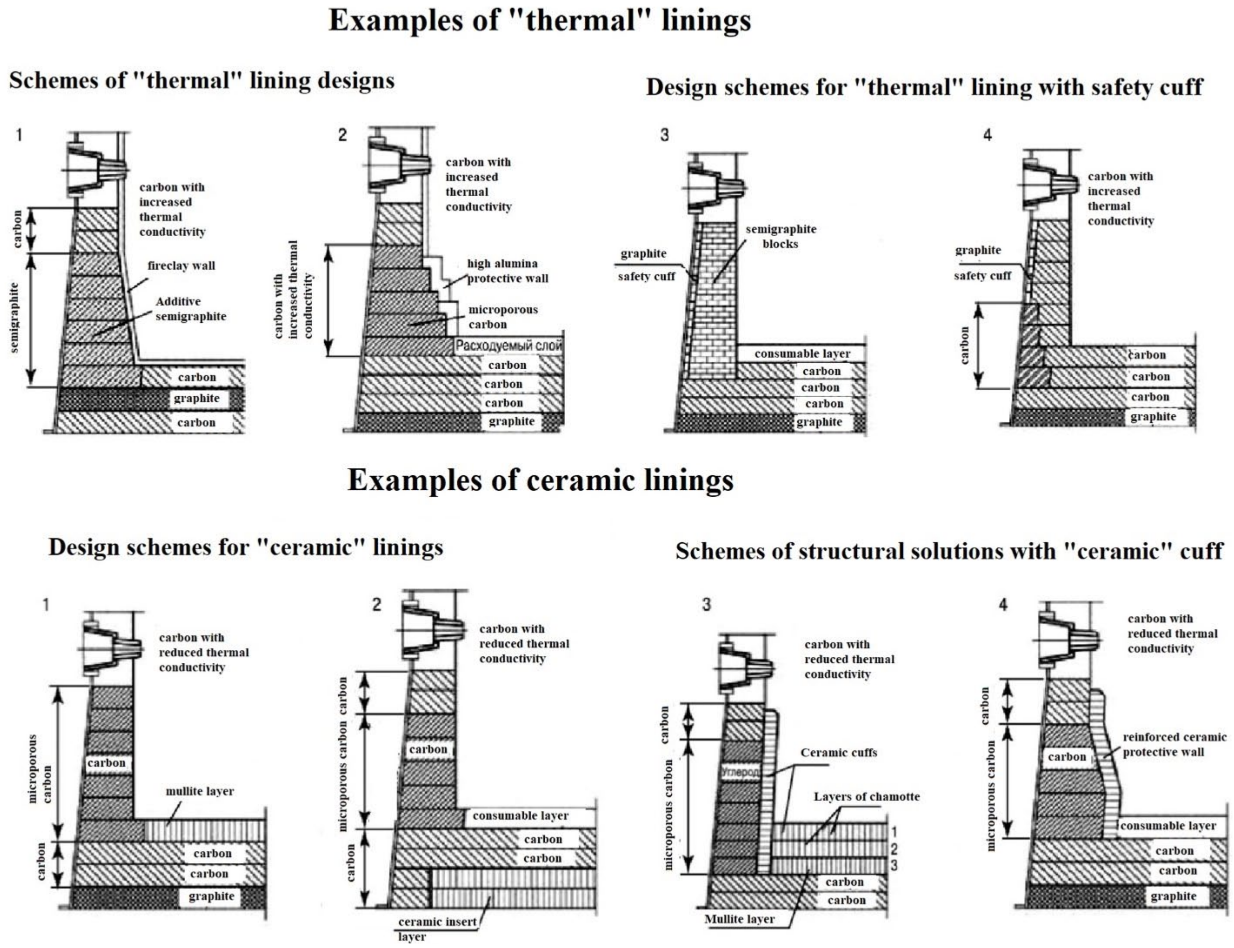

Fig. 1. Examples of different variants of "thermal" and "ceramic" lining [7]

others, have not received significant development in blast furnace production because of the dangers associated with increased radioactivity (isotope method), and with difficulties in technical implementation and the reliability of the results obtained [7].

Each of these methods has distinctive advantages and disadvantages (TABLE 1).

The conducted brief analysis shows that to date, there is no universal method that uniquely allows determination of the nature of lining erosion and formation of slag lining in the blast-furnace crucible [8].

2. Materials and methods

The ISI NASU is constantly developing in the interest of automated monitoring of residual thickness of the stack and slag lining of the blast furnace and hearth. At present, the systems for monitoring of thermal operation of the hearth are implemented at 10 blast furnaces (Automatic control system "Hearth") [9-10].

In the model, the approach developed by ISI NASU for determining the thermal condition and wear of the blast-furnace crucible liner is based on the combination of calorimetric and thermometric methods of control. This facilitates more qualitative determination of lining condition and slag lining formation in the blast-furnace crucible, allowing technologists to not only automatically control the condition of the cooling system, but also to influence a process of lining wear and slag lining formation.

To ensure reliable and functional operation of the automated control system "Hearth", 12-20 thermocouples are installed around the circumference of the furnace at 6-10 horizons of the blast-furnace crucible. The number of horizons and control points is determined by the design of the blast-furnace crucible and the possibility of installing a given number of thermocouples. Installation of thermocouples in the lining of blast-furnace crucible through the hollow bolt of the cooler plate or between the coolers plate is shown in Fig. 2. To install thermocouples in the carbon blocks of the hearthstone, the grooves between the cooling tubes are drilled to the appropriate length from inside the furnace. Then a metal tube with a dip-rod is installed. In the future, instead of a dip-rod, two thermocouples are installed in one tube (stainless steel tube with a diameter of 20×3 mm). Thermocouples, installed at different depths, are placed in the tube two by two (Fig. 3).

The peripheral cooling system requires the installation of resistance thermometers and flow meters to control the specific heat production from each blast-furnace crucible cooler, including the hot-metal taphole coolers. Subsequently, heat flows determined by thermocouples readings and specific heat production from coolers are used for automated control of lining and skull thickness in the blast-furnace crucible.

TABLE 1

Advantages and disadvantages of different methods of controlling the condition of the blast-furnace crucible

Control method	Benefits	Disadvantages
Core drilling	1. It allows to obtain the most accurate information about the condition and residual thickness of the lining and the thickness of the skull liner.	1. Violation of the amor integrity, the lining and the protective layer of the slag skull. 2. The possibility of conducting research only at long furnace stops, respectively, having a large periodicity of measurements. 3. No possibility of operational influence on the process of destruction of the lining and formation of slag skull.
Calorimetric	1. The measured heat flow gives the heat loss from the entire surface of the cooler or group of coolers. 2. The cooling systems of the blast-furnace crucible, thereby fully controlling the thermal condition of the hearth and the blast-furnace bottom. 3. Localized areas with increased heat loads and the degree of overgrowth or clogging of chiller tubes are identified.	1. Calculation of the residual thickness of the lining by thermal loads gives the average thickness of the line over the entire surface of the cooler; 2. Discreteness and laboriousness of determining heat loads measured manually, in the absence of automated control of temperature differences and coolant flow rates.
Thermometric	1. The ability to automatically determine the temperature of the line, its changes in height, perimeter and wall thickness of the blast-furnace crucible.	1. Difficulty in determining areas of local wear of the blast-furnace crucible liner that are not monitored by thermocouples.
Ultrasonic	1. Possibility to carry out express diagnostic analysis of the blast furnace crucible condition from any accessible place of the working platform of the metal collector. 2. Sufficient measurement accuracy. 3. The ability to determine the physical and mechanical characteristics of the lining (presence and parameters of cracks).	1. High cost of equipment. 2. High requirements for the quality of installation of equipment; the need for a large number of measurements. 3. Difficulty in organizing and carrying out measurements in automatic mode.

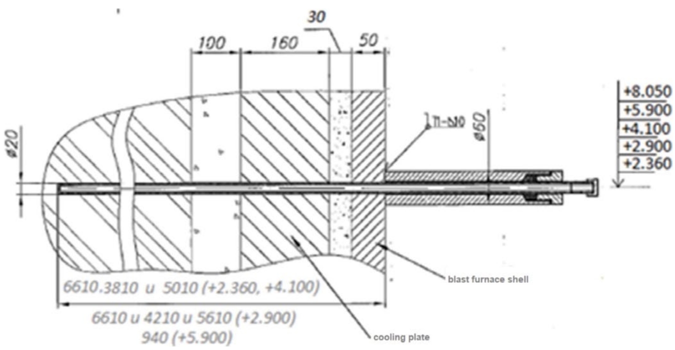

Fig. 2. Scheme installation of a thermocouple in the hollow bolt of the cooler in the cylindrical part of the blast-furnace crucible

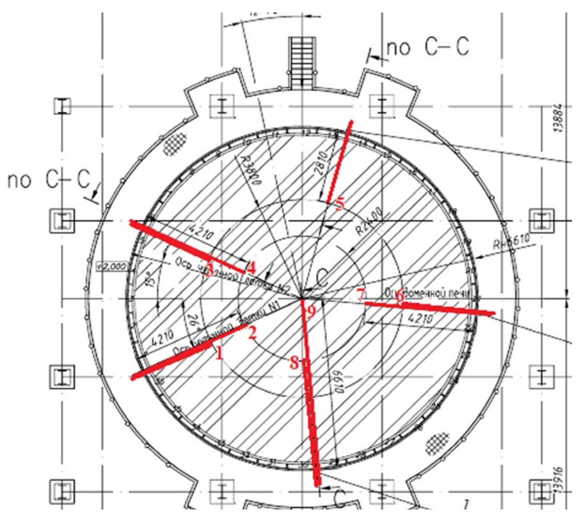

Fig. 3. Scheme of thermocouple installation in the centre of the blast-furnace bottom

Video frames of model "Hearth" implemented at BF No. 3 of "AZOVSTAL" are shown in Fig. 4.

3. Results and discussion

In Ukraine, during the reconstruction of blast furnaces, the preference was given to the design of blast-furnace crucible using a "ceramic cup". For the first time a blast furnace with this design of the hearth was made in 2008 at of "Arcelor Mittal Kryvyi Rih" at BF-8 and successfully operated until blowout in 2019. After 11 years of operation, the "ceramic cup" implemented by Saint-Gobain was preserved in the blast-furnace bottom (Fig. 2). In the future, the design of the blast-furnace crucible with a "ceramic cup" was successfully used at BF-3 of "Yenakiieve Iron and Steel Works", BF-3 of "Zaporizhstal", BF-3 and BF-4 of "AZOVSTAL".

However, even improvements in the design and cooling system of the blast-furnace crucible cannot fully provide an increase in the duration of the campaign without ensuring regular, and preferably automated, control of the hearth liner to assess the life of the furnace.

To assess the effect of design solutions on the condition of the lining (its wear rate and thermal loads), the thermal operation of 5 blast furnaces in Ukraine with different design of the blast-furnace crucible based on information from model "Hearth" was analyzed:

1) BF-8 of "Arcelor Mittal Kryvyi Rih" with the volume 2700 m^3 – Saint-Gobain ceramic glass, cooling system – process water (BF-8 Arcelor Mittal Kryvyi Rih);

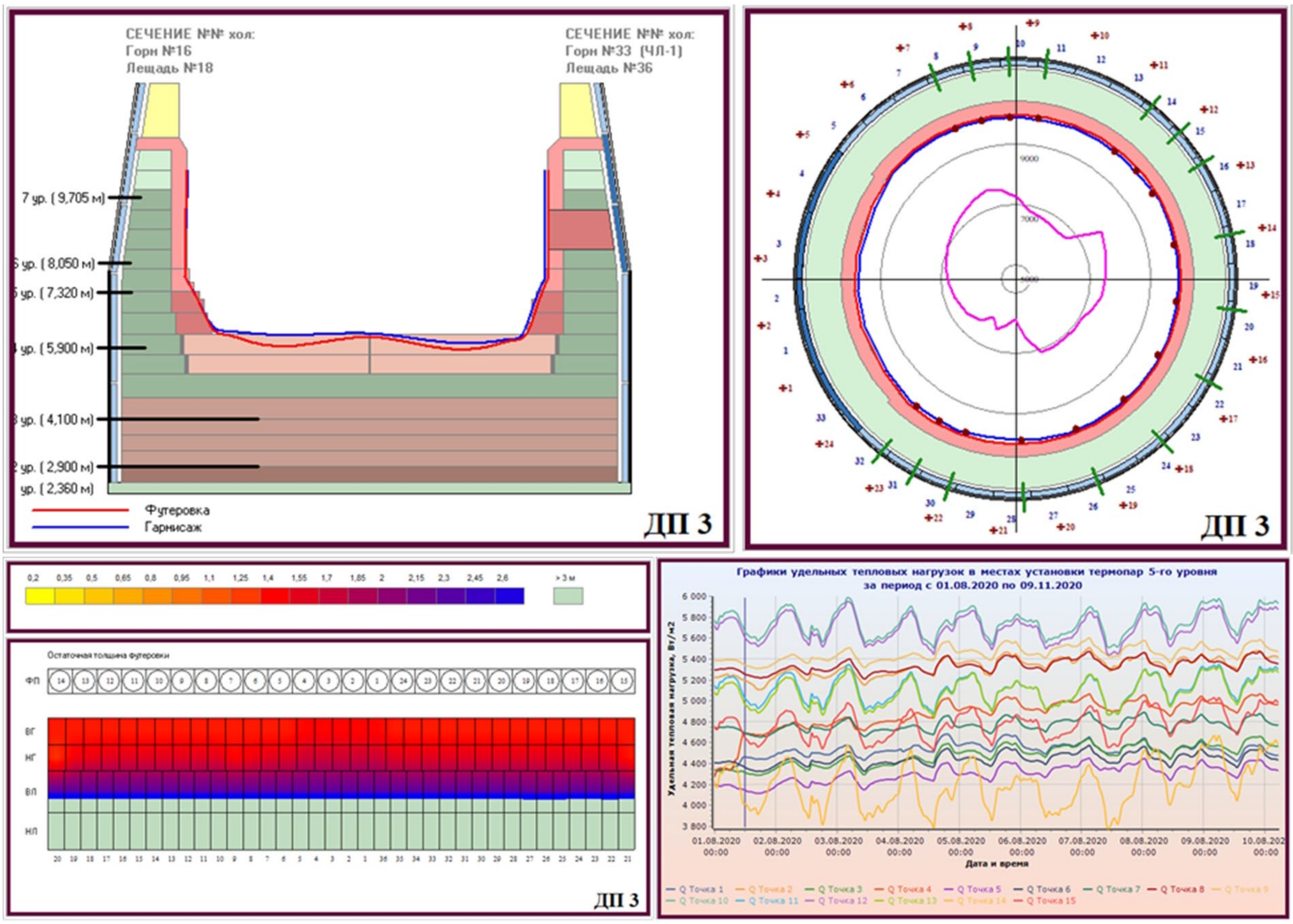

Fig. 4. Video images of the control system of lining glowing and formation of slag lining in the hearth furnace at BF № 3 of «AZOVSTAL» implemented in 2019-2020. (In the figure: Red line – lining thickness, blue line – skull thickness, pink line – heat load distribution)

Fig. 5. Photo of Saint-Gobain ceramic tumbler residue at the level of the 8th row of carbon blocks of BF-8 at "Arcelor Mittal Kryvyi Rih"

2) BF-3 of "AZOVSTAL" with a volume of 1800 m^3 – "ceramic cup" Gongyi Anzheng, cooling system – chemically treated water (BF-3 Azovstal);
3) BF-3 of "Zaporizhstal" with the volume 1513 m^3 – "ceramic cup" Gongyi Anzheng, cooling system – service water (BF-3 Zaporizhstal);
4) BF-4 of "Zaporizhstal" with the volume of 1513 m^3 – without "ceramic cup", cooling system – technical water (BF-4 Azovstal);
5) BF-2 of "Zaporizhstal" with the volume of 1513 m^3 – without "ceramic cup", cooling system – technical water (BF-2 Zaporizhstal).

It was found that high heat loads were observed at BF-8 of "Arcelor Mittal Kryvyi Rih", which is probably due to the large volume of the furnace. As a consequence, a large production and cooling perimeter of the blast-furnace crucible was observed. At the same time, BF-8 had the least wear of the lining in all areas of the blast-furnace crucible, except for the upper path of hearth (Fig. 4).

The difference in the wear rate of blast-furnace crucible and hearth bottom lining is determined by different intensity of blast furnace operation, their volume, construction and lining materials. For example, at BF-3 "Azovstal" in comparison with BF-3 "Zaporizhstal" there is a significantly higher wear rate of mullite blocks in the blast-furnace bottom (*area 1*) despite the fact that both furnaces use "ceramic cup" Gongyi Anzheng. In addition to the intensity of blast furnace operation, this is due to the fact that different mullite blocks are installed on the furnaces (at "Azovstal" – GSBFCUP-80, at "Zaporizhstal" – GSBFMLD-63).

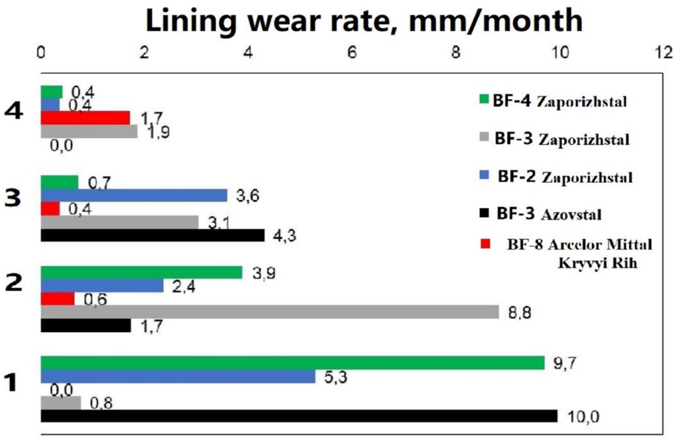

Fig. 6. Thermal loads and rate of lining wear on blast furnaces of various designs for two years from blowing: 1 – cooling of the lower part blast-furnace bottom; 2 – cooling of the upper part blast-furnace bottom; 3 – lower part of the hearth; 4 – upper part of the hearth

Less lining wear at BF-8 "Arcelor Mittal Kryvyi Rih" in comparison with other furnaces with "ceramic cup" is connected with lower intensity of blast furnace operation, absence of pulverised coal fuel application, as well as thermophysical properties of ceramic lining.

Since heat loss is an integral parameter that allows qualitative and quantitative assessment of thermal performance of controlled zones and the furnace as a whole, a comparison of heat losses in the cooling system of considered blast furnaces was performed (Fig. 7) [10,11].

It was found that large heat losses ~1.4-1.8 MW were observed at BF №8 of "Arcelor Mittal Kryvyi Rih", BF №2 and BF №4 of "Zaporizhstal", smaller – ~0.9-1.3 MW – at BF №3 "Zaporizhstal" and BF №3 "Azovstal".

However, the usual comparison of heat losses does not allow us to assess the impact of furnace design on the thermal performance of the hearth and the hearth, due to the different volume of blast furnaces and, as a consequence, the different volume of cast iron produced. Therefore, the specific value of heat losses of blast-furnace crucible per unit volume of furnace was estimated (Fig. 8).

The value of specific heat losses per unit volume of blast furnace at blast furnaces with a "ceramic cup" (~0.4-0.7 kW/m^3) is significantly lower than at blast furnaces

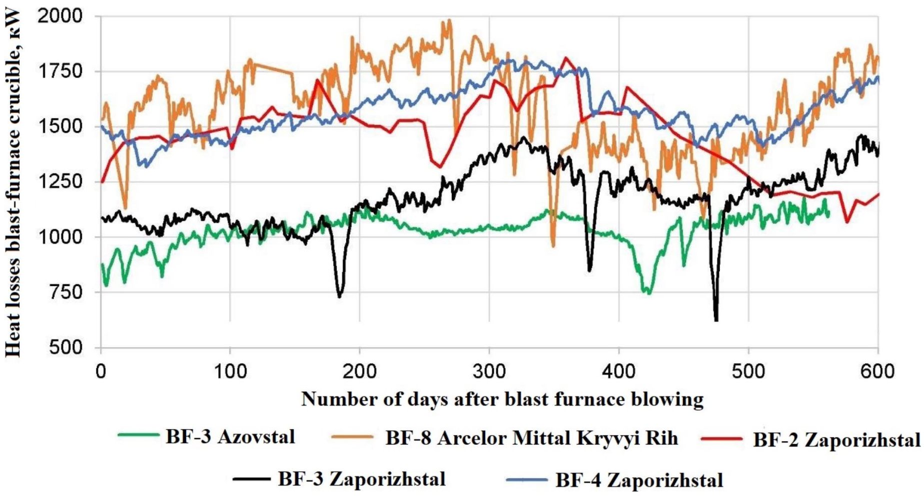

Fig. 7. Dynamics of heat losses in the hearth of blast furnaces in Ukraine

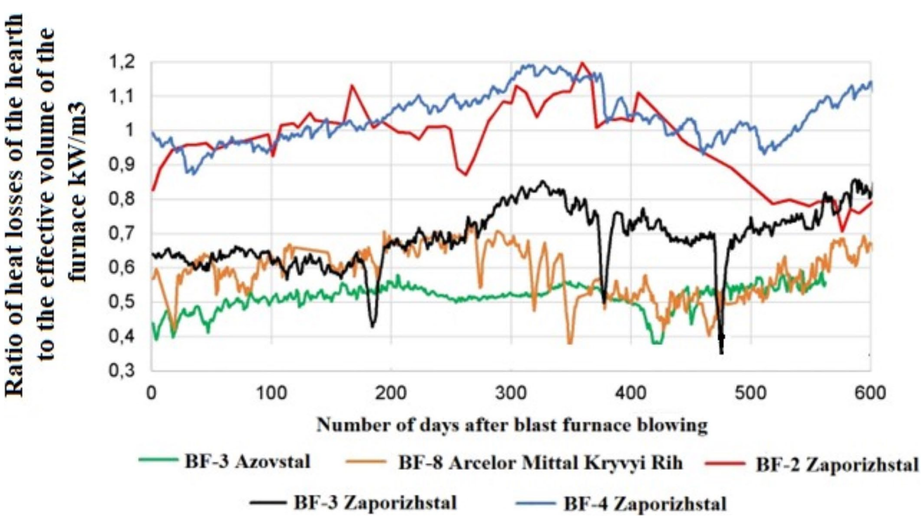

Fig. 8. Dynamics of specific heat losses of the hearth per unit volume of the blast furnace

without it (~0.9-1.1 kW/m^3). Such difference between specific heat losses corresponds to 0.5-1.1 kg/t-HM less coke consumption to compensate for heat losses from hearth at blast furnaces with ceramic stack (Fig. 8).

Thus, it was found that the generalizing parameter for comparing the thermal performance of blast-furnace crucible is the specific heat loss per unit of useful volume of the furnace.

4. Conclusions

1. One of the main points of safety and ensuring the duration of the blast furnace campaign is automated real-time monitoring of the thermal state of the peripheral and blast-furnace bottom cooling system, monitoring the temperature of the line of the blast-furnace crucible.
2. The model "Hearth", installed at more than 10 blast furnaces was used to compare heat losses of various crucible designs. The model is based on a combination of calorimetric and thermometric methods of control proposed by ISI NASU for monitoring thermal conditions and wear of the hearth lining.
3. It is established that the generalizing parameter for comparing the thermal conditions of blast-furnace crucible is the specific heat loss per unit of useful volume of the furnace.
4. Implementation of continuous control over the wear of the hearth lining on blast furnaces allowed estimation of the effect of using a "ceramic cup" in terms of the value of heat losses of the hearth. The value of specific heat loss per unit volume of blast furnace with "ceramic cup" (~0,4-0,7 kW/m^3) is significantly lower than at blast furnaces without it (~0,9-1,1 kW/m^3). This difference between specific heat losses corresponds to a lower coke consumption of 0.5-1.1 kg/t-HM for compensation of hearth heat losses at blast furnaces with "ceramic cup".

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