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An attempt to specify the degradation of the electric furnace hearth for the determination of future operating properties

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ABSTRACT

Purpose: of this paper is the analysis of potential use of new materials in the electric furnace hearth lining and indication of the operating effects for the furnace resulting from their use. The impact of the application of new hearth lining materials on a total power needed to receive through air cooling system of the furnace hearth was also analyzed.

Design/methodology/approach: Within the frameworks of research, electric furnace operational properties were compiled and a furnace mathematical model on the basis of the finite element method was created. Based on operational data the created model was calibrated. Analysis of the influence of new hearth lining materials on the furnace operation was performed. In analysis the change of materials properties resulting from the furnace operation over the years was taken into consideration.

Findings: As a result of carried out calculations and analysis the amounts of heat flux transferred, in successive periods of operation, through hearth working layer to cooling installations were acquired. Basing on simulations and calculations, for the above mentioned heat flux, temperatures were calculated on the bottom shell of furnace, in the electrodes axes for different periods of furnace operation.

Practical implications: To achieve a decrease in thermal load of hearth it is advisable to reduce thickness of filling material near the vertical wall of furnace and filling the acquired space with new graphite blocks applied to the last layer of hearth. Those information were crucial and had an actual impact on a final design of furnace lining.

Originality/value: Carried out analysis have crucial meaning for furnace user, as they allow to predict the probable operation of furnace with new lining materials over the years. This will also make it easier to control the state of lining materials wear and will allow for a better process control.

Keywords: Technological devices and equipment; Electric furnace; Metallurgy of copper; Working properties of materials and products

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

One of the stages of copper production is recovery process in which copper is recovered from the metallurgical slag. In contemporary smelters this process is carried out in an electric furnace. As a result of reactions taking place in the furnace a separation of the CuPbFe melt and the slag located above occurs. The slag is removed from the furnace and CuPbFe melt is a semi-finished product for further processing.

The construction of the furnace is of conventional design. The interior of the furnace is lined with refractory materials and the outer surfaces are cooled down. The walls of the furnace are cooled by a water cooling system, while the hearth by the air cooling system.

Together with furnace operation there is a visible degradation of insulating materials that affects the way of process control as well as has an impact on economic efficiency. Applied insulating materials have undergone wear from chemical reaction between the gas and the melt. This caused a reduction in thickness of insulating materials, and consequently greater heat loss.

In the furnace hearth, as a result of operation time, saturation of insulating materials with melt occurs. This phenomenon causes multiple increase of thermal conductivity and consequently larger amounts of heat flow from the inside of the furnace to the bottom of the furnace. As a result, a cooling of the melt takes place. Along with time, the impact of this phenomenon is increasing.

2. Research methodology

After years of operation in the described furnace a major repair was planned. Within repair works all insulation materials had to be replaced. However, not all insulation materials produced two decades ago are produced today.

The aim of the analysis was to evaluate the possibility of using modern hearth lining materials in place of the worn out with different properties. To realize this objective it was decided to perform numerical calculations of new materials operation and their impact on the entire furnace.

Within the research a comparative analysis of the furnace hearth thermal operation for the currently operating furnace and for the furnace with new hearth lining materials was performed. New materials were provided to be applied in electric furnace hearth lining during the major repair.

In the comparative analysis the influence of time on the main hearth insulating material change was taken into account. Numerical calculations were performed using finite element analysis software. These calculations included the construction of the model, description of material properties, determination of the boundary conditions and the execution of numerical simulations of the furnace with currently used and new materials. The furnace operational time was decided to be described with the varying properties of the material. These variables described the wear and thermal operational parameters. Within the calculations also the simulation results of the furnace with severely worn hearth lining materials with operating data were compared.

2.1. Input data

Over the years, the method of controlling the process in the furnace and the method of furnace hearth cooling the furnace construction solutions have undergone major changes. Initially, hearth cooling was carried out using the full power of the fans. Thereafter, transmission was introduced with the aim of reducing cooling efficiency. Next, the frequency converters were used to control capacity of the fans. Capturing these changes is difficult and description on the basis of measured data and the parameters of the cooling air in the channels under the hearth is burdened with major inaccuracies. Also, the source of thermal energy supplied to the furnace has changed. After a few years of operating furnace transformer was replaced by the new with greater power, which also has changed the parameters of the furnace.

These changes and their impact on the furnace behavior, in particular the heat removal process characteristics, forced the acceptance of some medium states to enable the construction of models. Variability of the furnace operating conditions over the years has made it impossible to create a single model that will take into consideration all the phenomena. Therefore it was decided, after analysis of available data received from furnace user to describe the three states of the furnace:

- the first model of the furnace is an attempt to describe its work soon after the furnace hearth lining replacement - after about 6 months,
- the second model describes the furnace operating parameters after several years of work,
- the third model refers to the furnace with severely worn hearth lining.

The furnace operating parameters, which were also boundary conditions for numerical simulations, were obtained from furnace user. Adopted parameters for the above mentioned three states of furnace relating to the temperature under the working layer of hearth lining, the hearth bottom shell temperature and the power received by the hearth are shown below in Table 1.

Table 1.
Average data characterizing different furnace operating states (Furnace soon after repair; Furnace after several years of work; Furnace with severely worn hearth lining)

	Furnace after a major repair	Furnace after several years of operation	Furnace with severely worn hearth lining
T_1^* [^{o}C]	220	320 (300-340)	390-410
T_2^* [^{o}C]	90	150 (120-180)	200-230
P^* [MW]	0.9-1.1	1.4-1.6	2.5-2.7

* T1 - temperature under the working layer of hearth lining,
T2 - the hearth bottom shell temperature,
P - power received by the hearth

2.2. Thermal properties of applied materials

For the purpose of electric furnace numerical simulations properties of materials used in the construction of currently operating furnace and materials for a new hearth lining were collected. For currently operating furnace in the numerical simulation the following materials were applied: refractory products ANKROM S-55, ANKERFILL GT05, MCV, BOS, graphite products MGO and WGH-67.

The properties of materials applied in the furnace during the major repair are partially not available - out of production or replaced by newer products with different trade names. For purposes of this analysis data was obtained from manufacturer's archive materials and offers [1-4].

For the model with new hearth lining materials properties of these materials provided to be applied during the major repair were taken into account [5]. Electric furnace hearth consists of two main layers. The first layer is the hearth working layer of S-55 material and its aim is thermal insulation. The second layer is a graphite material which task is homogenization of the working layer temperature and further the melt temperature.

Hearth lining materials, their positioning and various ways of furnace cooling are show in Figure 1.

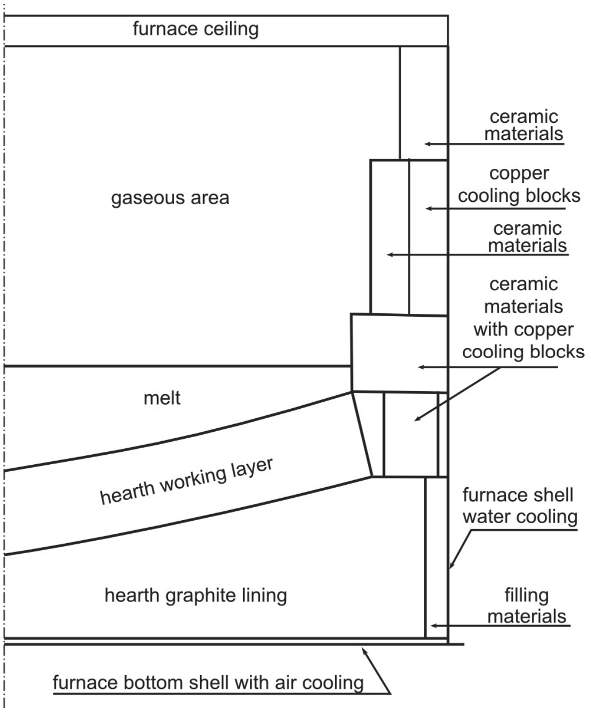

Fig. 1. A furnace intersection with various ways of cooling and insulating indicated

An important issue for the thermal analysis of the furnace operation was the varying thermal conductivity of the furnace hearth working layer [6]. With the furnace operation time a degree of saturation S-55 by a melt is arising and heat conductivity for this material is increasing. Therefore it was necessary to create thermal conductivity curves taking into account the saturation by melt.

When deriving the material S-55 thermal properties models it was assumed that the material will undergo a progressively greater saturation until the maximum internal voids filling capacity with melt is reached. According the manufacturer porosity and thus the number of voids in the material amounts 16% +-1%. The internal air-filled voids are not connected with a network of tubules that would allow a free flow of melt. However the head of the melt inside the hearth is alternately being frozen and melted over again due to „pulsations" occurring in the cross section of the hearth. Copper state of aggregation change is accompanied by change in its volume causing internal stress and later on local crushing of the walls between the bubbles. The research photos from furnace user reveal a layered arrangement of the copper sections confirming the nature of the phenomenon described in [7]. That phenomenon affects the material S-55 air voids merger, the subsequent filling of them with melt and creation of heat leakage bridges.

Created under the above assumptions the thermal conductivity curves for the three different degrees of furnace hearth lining wear are shown in Figure 2.

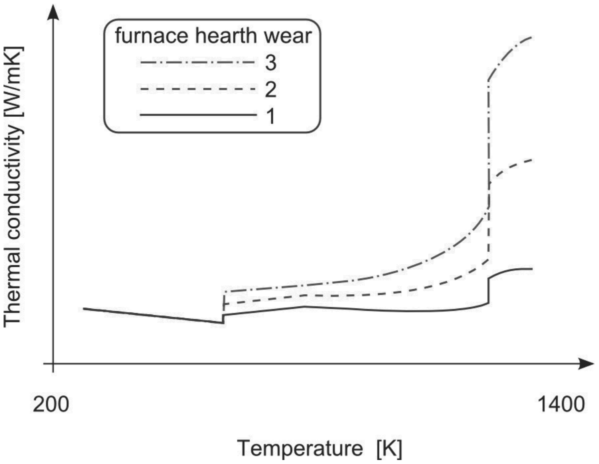

Fig. 2 Dependence of S-55 thermal conductivity on temperature for three different degrees of furnace hearth lining wear. 1- new furnace lining, 2 - furnace lining after several years of operation, 3 - severely worn lining

3. Numerical simulations of the electric furnace operation

3.1. Model calibration

Before the numerical simulations and calculations of a furnace with new lining materials could be started the model needed to be calibrated so that it would represent the parameters of furnace that is currently in operation. To do that a number of models were developed. Those models represent different states of a furnace lifecycle (wear degree) and corresponding work parameters. Temperature under the working layer of graphite lining, temperature on the furnace shell and power going through furnace hearth were chosen as main parameters needed for the model calibration. After achieving results similar to furnace operation parameters, that were obtained from the user, the simulation was recognized to be calibrated.

Models that were chosen for calibration reflect different degrees of furnace hearth lining wear. The first model shows the furnace with a new lining materials after just several months of work. In the second model the first layer of furnace hearth is soaked with melt as it would be after several years of furnace operation. The third model represents furnace with worn out lining (all voids in first layer of lining material filled with melt).

The results of calibrating simulations are presented in Table 2. Sample temperature and heat flux distributions are shown in Figures 3 and 4.

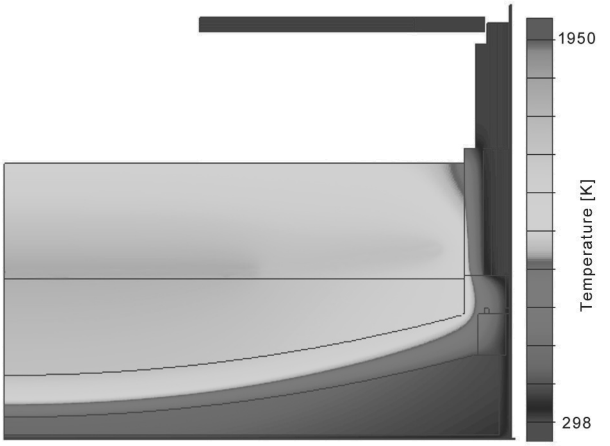

Fig. 3. Temperature distribution for the furnace after several years of operation

Fig. 4. Heat flux distribution for the furnace after several years of operation

Due to the calculate on results convergent with the parameters of furnace thermal operation received from the user it was stated that boundary conditions adopted for the analysis are valid and the developed model allows to specify future operation of the furnace.

Model calibrated in such way was a base for further analysis with new graphite lining materials taken into consideration. Those materials are supposed to be used after the furnace major repair. An influence of those new materials on auxiliary installations was also analysed (way of heat transfer through furnace hearth and cooling water streaming on furnace side shell).

Table 2.
Calculated temperatures in characteristic points of installation (T1 - temperature under the working layer of hearth lining, T2 - the hearth bottom shell temperature) and power (P) collected by the cooling installation in relation to data received from the user)

	Furnace after a major repair	Deviation from user data	Furnace after several years of operation	Deviation from user data	Furnace with severely worn hearth lining	Deviation from user data
T1 [^oC]	228.9	4.05%	310.33	3.02%	401.18	0.29%
T2 [^oC]	89.33	0.74%	124.11	17.26%	229.47	6.73%
P [MW]	1.15	15.00%	1.41	6.00%	2.76	6.15%

3.2. Comparison of the furnace with new and worn hearth lining materials with the variant analysis of graphite layers positioning

Simulations of furnace operation with new graphite materials were carried out for four different variants. Those simulations varied in positioning of the last graphite layer in hearth. Also thickness of graphite filling material varied.

The first variant assumed hearth lining with new materials in a way that bigger values of thermal conductivity would be positioned perpendicular to furnace bottom. Side part of furnace hearth was filled with new graphite filling material.

In the second variant model, new graphite materials were positioned in a way to guarantee bigger values of thermal conductivity parallel to furnace bottom. The new graphite filling material was positioned in the same way as in variant 1.

The third variant, not only had new graphite material oriented parallel to furnace bottom, it also had an additional layer of this material near the side of furnace. This additional layer had been aligned in a way that bigger values of thermal conductivity would be provided in parallel direction the side of furnace. Also, the new filling material layer thickness was reduced.

Fourth and last variant had its materials oriented so that it would provide bigger values of thermal conductivity parallel to the bottom of furnace in both layers near furnace bottom shell.

Above described variants are presented in Figure 5.

A series of simulations had been carried out for above mentioned variants. As a result, temperature fields in furnace hearth, heat flux fields and power transferred to cooling installations through bottom and sides of furnace, had been obtained.

Matching the results of simulations of furnace with old lining materials and with four variants of new lining materials alignment is presented in Table 3.

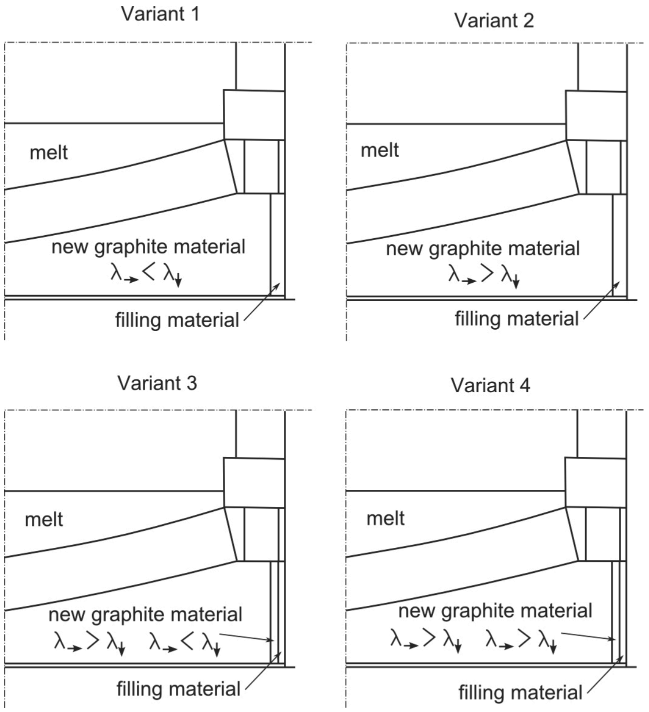

Fig. 5. Variants of new hearth lining materials positioning

Table 3.
Matching of power transferred through bottom and sides of furnace to cooling installations depending on simulation variant

	Current furnace		Variant 1		Variant 2	
	P [MW]	[%]	P [MW]	[%]	P [MW]	[%]
$P_{\text{through hearth}}$	2.76	86.06	2.542	78.34	2.515	77.70
$P_{\text{through sides}}$	0.447	13.94	0.703	21.66	0.722	22.30
P_{total}	3.207	0.00	3.245	1.18	3.237	0.94
Thermal load decrease	0	0.00	-0.218	-7.90	-0.245	-8.88

	Current furnace		Variant 3		Variant 4	
	P [MW]	[%]	P [MW]	[%]	P [MW]	[%]
$P_{\text{through hearth}}$	2.76	86.06	2.448	75.53	2.445	75.39
$P_{\text{through sides}}$	0.447	13.94	0.793	24.47	0.798	24.61
P_{total}	3.207	0.00	3.241	1.06	3.243	1.12
Thermal load decrease	0	0.00	-0.312	-11.30	-0.315	-11.41

Based on presented results, a conclusion can be made. Total heat flux transferred through hearth and collected by cooling installations for furnace with new materials increase only by 0.94-1.18% in relation to current state. Such increase is negligible at such a significant difference in the thermal conductivity of a new graphite in comparison with the graphite used today.

For the range of operation temperatures, thermal conductivity of the new graphite material proposed for use in last layer is much higher (varying from 1.52 to 1.15 times greater) than for previously used material.

Such increase in thermal conductivity, despite negligible increase in heat flux, has an impact on furnace hearth operation characteristics. Increased thermal conductivity causes hearth temperature to have more uniform distribution comparing to hearth with old graphite lining materials. The high conductivity will also affect heat transfer in the central part of furnace causing more heat to be transferred from this part to external areas.

Applying new materials for furnace hearth lining allows to decrease thermal load of hearth by 7.9-11.41%. In variant 1, where the highest values of thermal conductivity coefficient of the new graphite material are positioned perpendicular to furnace bottom, thermal load of hearth is decreased by 7.9%. Changing the direction of graphite materials orientation allows, by increasing heat transfer towards the sides of furnace, for further decreasing of hearth thermal load to the value of 8,88% comparing to the old furnace. Using, in variants 3 and 4, an additional layer of filling material, causes a significant decrease in hearth thermal load. Regardless of the direction in which the adjacent layer of graphite material is positioned, there is no significant difference visible in decreasing hearth thermal load. For variant 3, decrease in hearth thermal load, compared to the furnace with old materials, is 11.3% and in case of variant 4, a small increase in hearth unloading is observed to value of 11.41%.

After concluding variants 3 and 4 to be the most profitable from the point of transferring some of the heat from furnace hearth to its sides it was decided to base further calculations upon those variants. Those further calculations included an analysis of the furnace during its operation with new materials used for hearth lining, including changes in thermal properties due to progressive soaking of graphite materials with melt.

3.3. Simulations of furnace operation with new lining materials for the chosen graphite layers positioning

When starting simulations it was necessary to choose one specific variant for further analysis. As the difference between variants 3 and 4 is only 0.11% in matter of decreasing hearth thermal load, variant 3 has been chosen for further analysis as to be less favourable.

During creation of the model, increasing soaking of graphite material with melt was taken into consideration. It was expressed by three states of lining material wear. Those states were: new lining (after a major repair), lining materials partly used (after a few years of operation) and worn out lining materials.

Temperature fields and heat flux distributions and power collected by cooling installations for three different states of lining materials wear were acquired as a result of the simulations. Above mentioned results are shown below in Figures 6 and 7.

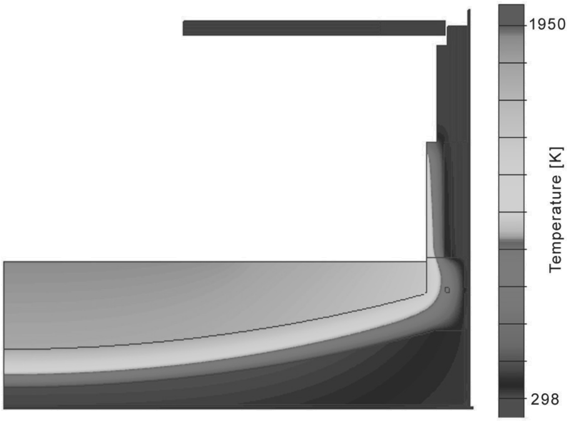

Fig. 6. Expected temperature field for a new furnace - straight after a major repair and lining materials replacement

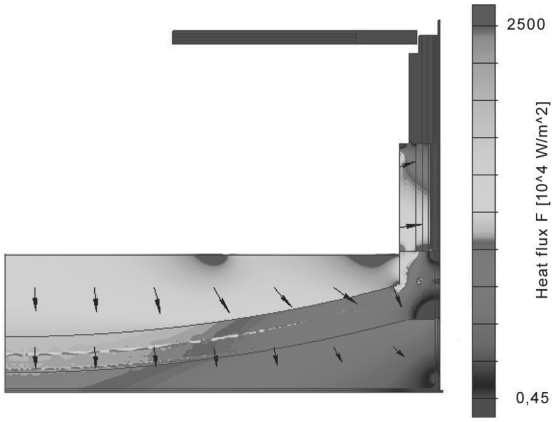

Fig. 7. Expected heat flux distribution for a new furnace - straight after a major repair and lining materials replacement

4. Summary and conclusions

As a result of carried out simulations and calculations a mathematical model of currently operating furnace that represents operational parameters at different stages of normal operation (excluding break down situation) was performed. Within the research a comparative calculations of different configurations of hearth graphite materials positioning were conducted. Furthermore simulations of a furnace with new graphite materials applied to hearth were carried out.

Basing on carried out works it can be concluded that:

- due to variability of operation parameters (changes in hearth cooling control, exchange of transformer) it is not possible to build one coherent model describing operation of electric furnace hearth during the whole lifecycle,
- due to a small value of the anisotropy of thermal properties, the way of preparation of graphite blocks for application in the furnace hearth, has negligible importance,
- to achieve a decrease in thermal load of hearth it is advisable to reduce thickness of filling material near the vertical wall of furnace and filling the acquired space with new graphite blocks applied to the last layer of hearth,
- power needed to be collected by cooling installations varying for different operation periods of the furnace was calculated as a result of simulations
- based on the acquired heat flux distributions, average temperatures were calculated on the bottom shell of furnace, in the electrodes axes for different periods of furnace operation.

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