BLAST FURNACE HEARTH MULTIDIMENSIONAL WEARING MODEL[1]

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Abstract
Blast furnace campaign has been determined by hearth refractory line lifetime, this way, it is very important a systematic follow up of wearing evolution to avoid to interrupt the campaign prematurely or to extend it until a safe limit. The refractory thickness measurement and skull thickness is difficult to be carried out directly during the blast furnace operation, with that the mathematical heat transfer model is a powerful tool to quantify the wearing based on the evaluation of the 1150 ºC isotherm. In this work, a heat transfer axially symmetrical wear model based on finite element method and the Gauss-Newton interactive method were developed. The simulation results based in the model with the purpose to evaluate the Gerdau Açominas blast furnace 1 hearth wearing were shown quite coherent, evidencing to be a powerful tool to be used.
Key words: Blast furnace; Hearth; Model; FEM.

MODELO MULTIDIMENSIONAL DE AVALIAÇÃO DO DESGASTE DE CADINHO DE ALTO-FORNO

Resumo
A campanha dos altos-fornos tem sido determinada pela duração do revestimento refratário do cadinho, desta forma, é muito importante um acompanhamento sistemático da evolução do desgaste, para se evitar interromper prematuramente a campanha ou estendê-la até um limite seguro. A medição do refratário remanescente e da camada agregada é difícil de ser realizada diretamente durante o funcionamento do forno, com isso o modelo matemático de transferência de calor é uma ferramenta poderosa para quantificar o desgaste baseada na avaliação da isoterma de 1150°C. Neste trabalho, um modelo de avaliação de desgaste simétrico axialmente de transferência de calor baseado no método de elemento finito e o método interativo Gauss-Newton foi desenvolvido. Os resultados de simulação baseados no modelo com o propósito de avaliação do desgaste do cadinho do alto-forno 1 da Gerdau Acominas, se mostraram bastante coerentes, evidenciando ser uma ferramenta poderosa para qual foi proposto.
Palavras-chave: Alto-forno; Cadinho; Modelo de desgaste; Elementos finitos

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1 INTRODUCTION

The improvement of blast furnace operation and maintenance and the technological advances of the new projects caused an increase in productivity, the reduction of fuel consumption, an improvement in the hot metal quality, and the extension of the equipment's useful life. Besides taking special care during the project development and construction, the establishment of a reliable hearth wear monitoring system is vital to determine the residual thickness of the refractory lining, which provides operational safety to the decision-making process in order to avoid premature wear or a serious accident.

Traditionally, the hearth is monitored by a thermocouple assembly. The heat flow and the refractory thickness in relation to each position can be calculated by mathematic models if precise data about the location of the thermocouple and the charcateristics of the furnace lining materials are gathered, which would allow us to determine the hearth wear profile. The models may be simple, such as the monodimensional, or complex, such as the three-dimensional.

2 OBJECTIVE

To develop a two-dimensional mathematical model to calculate the blast furnace hearth refractory lining temperature profile, and from the 1150^{o} C isotherm, to estimate the remaining carbon blocks wear profile. The model must be appropriate for industrial use. The follow-up allows for the counteractions required to extend the blast furnace useful life to be taken, besides estimating its campaign. The model may also be used to select the most appropriate location for the salamander tapping at the end of the campaign.

3 BIBLIOGRAPHIC REVIEWS

A bibliographic review for practical application was done to verify the most appropriate method for industrial hearth monitoring. In the past, several methods were used to wear evaluation. Among them is the use of radioactive bits inserted in the carbon block at depths determined according with Shultz et al (1974) and Perco et al (1974), and using electric cables previously installed in the wall lining or in the bottom of the hearth according with Sakamoto et al (1982). Another recently used method is the acoustic resonance technique to measure the remaining refractory thickness. According to Zulli et al (2003), the method envolves exciting a refractory block acustically applying a senoidal force. A vibration sensor mounted on an adjacent bar detects the acoustic response. The refractory length (or thickness) is determined by the speed of sound in the refractory and the resonance frequency determined for the block. The core bore method is also used to verify the integrity of the remaining carbon blocks. According with Tallat et al (2005), the carbon blocks' deterioration temperature is 538^{o} C. From this point, they start to lose their properties. The sampling process consists in drilling to determine the intact section of the block. Nowadays, the most used hearth assessment is done by determining the heat flow. It can be done directly with the application of some kind of calorimeter or another type of mesuring device, and indirectly, applying Fourier's law with previous knowledge about the thermal conductivity of the materials and temperature values located inside the hearths lining. The heat flow measurement can also be done by the cooling system water flow and temperature (Ferreira, 1992).

3.1 Finite Element Method (FEM)

The finite elements method is the most common technique to estimate hearth wear. It consists in dividing the calculation domain into several sub-regions called finite elements. One set of equations is solved for unknown values in the points (notchs), considered to represent these sub-regions. It is necessary to consider the entire domain, because the integration is performed over the entire region. The only problem of the FEM is the need of good computation resources to solve the model.

3.2 Inverse Problems

Inverse problems are understood as those arising from the attempt to determine the causes by means of the effects observed. Mathematically, inverse problems belong to the ill-posed problem class. Hadamard has defined that a well-posed problem fulfills all of the three conditions: (i) it has a solution. (ii) there is only one solution; (iii) the solution is continuously dependant on the data entered. Usually, none of the conditions is satisfyed in an inverse problem. In general, the observations are not precise (the data is contaminated by noise or experimental error) and incomplete.
Several techniques were developed in the last years to by-pass the ill-posed issue of inverse problems aiming at obtaining a stable solution for such problems. Some solution methods proposed by Velho (2005) are: direct reversion, decomposition in singular values, minimum squares and variables (minimum weighted squares), regulation methods, differential methods and others.

3.2.1 Regulation methods

The regulation method consists in determining the lowest approximate solution compatible with the observation data for a particular noise level. The Tikhonov regulation, cited by Velho (2005), is one of the most common regulation methods for ill-posed problems. The mathematic implementation is formulated as an optimization problem:

$$\min\left\{\left\|A(u)-f^{\delta}\right\|_2^2+\alpha\left\|\Omega[u]\right\|\right\} \qquad (3.1)$$

Where:

$A(u)-f^{\delta}$ Represents the direct model;
$\Omega[u]$ is the regulation operator;
α is the regulation parameter.

Beyond the problem of the instability and the existence of local minimums, the convergence of this method to solve I'll posed problem can be very slow. In this direction, Alves et al (2005) cited that Newton, Levenberg-Marquardt and Gauss-Newton iterative methods can be a more interesting alternative. Gonzales et al (2004) developed hearth wear model based on Gauss-Newton iterative methods.

4 METHODOLOGY

As described in the bibliographic revision, there are several wear models adopted to estimate the hearth wear. In this model, the aim is to identify the erosion profile with the 1150° C isotherm position, obtained from the heat transfer in the hearth refractories where this line represents a potential limit of the pig iron penetration inside the hearth wall because of the refractory porosity. The model is divided into direct problem and inverse problem, where the direct model uses the elements technique to estimate the temperature profile for a particular line of wear and the Inverse is responsible for diminishing the difference between the thermocouple temperature and the temperature calculated by the direct model, proposing a new wear line.

4.1 Problem Characterization

The Gerdau Açominas blast furnace is considered to be of a medium to a large size. Its internal volume is 3051 m³; and the daily production is approximately 8000 t. The first blast furnace campaign was undertaken between 1986 and 1994, and the revamp was undertaken in September 1994, when the furnace was entirely rebuilt. In 2001, the second revamp was undertaken, but this time the hearth wasn't repaired. In order to minimize the model failures, the thermal conductivity was used as a function of the temperature defined by the manufacturers from tests carried out in samples from the materials supplied. The Figure 1 presents the hearth project with the respective materials and the thermocouple location.

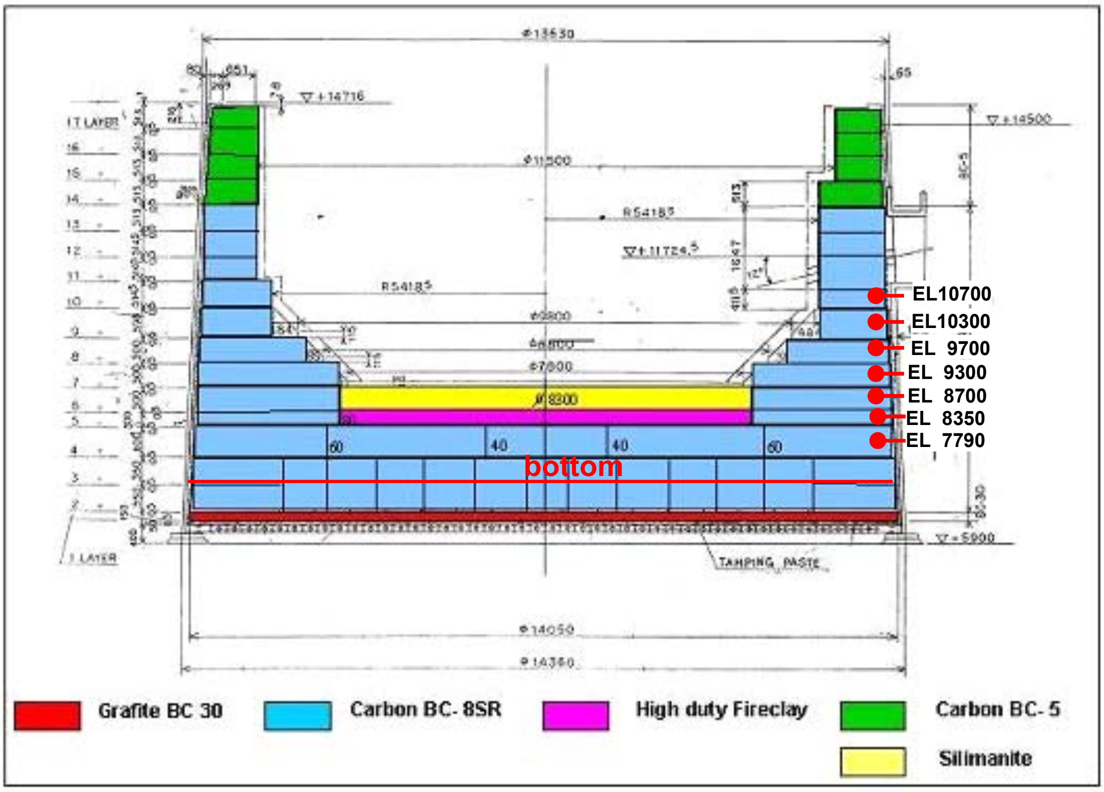


Figure 1: Gerdau Açominas blast furnace No. 1 hearth

4.2 Mathematic Equations

The stationary heat conduction problems or the Fourier law are characterized by the following differential equation (4.1):

$$\nabla \cdot (k \nabla T) = 0 \qquad (4.1)$$

Where K is the thermal conductivity and the symbol ∇, ***nabia***, is the vector differential operator.
For the axially symetric two-dimensional problem in cilyndric coordinates**,** the following equation (4.2) is generated:

$$\frac{1}{r} \cdot \frac{\partial}{\partial r}\left(k \cdot r \cdot \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z}\left(k \cdot \frac{\partial T}{\partial z} \right) = 0 \qquad (4.2)$$

Where K is the thermal conductivity and r and z are values in meters (m) in the radial and vertical directions, respectively.
The boundary conditions consider the absence of a zero heat flow in the interface between the iron notch and the upper limit of the hearth side wall. In relation to the hearth base and wall, the heat flow was estimated by the double and triple thermocouple historical values, and the internal temperature on the wear curve corresponds to the 1150^o C isotherm. In order to obtain a general solution, so to by-pass the problem, the hearth region was divided into sub-regions, varying only the dimensions according to the wear position and the desired refinement in relation to the number of pre-established elements. The nodes will undergo some distortions for the discretization, so that the location of the nodes and the thermocouples coincide and so that the transitions of different kinds of materials in one same element occurr in diametrically opposed notchs. In both these cases, the distortions are supposed to avoid interpolation in the temperature calculation to be compared with the temperature of the thermocouple in the same location, and to facilitate the weighting of the thermal conductivity equivalent in the solution calculation.

4.3 Inverse Problem Model

The 1150^o C isotherm position is estimated from the thermocouple records existing in the hearth, solving an estimation inverse problem so that the temperatures calculated by means of the thermal transference finite elements technique coincide with the thermocouples measurements. Since the problem has a finite dimension, it means that not only the number of measurements of the thermocouples is finite, but also the parameters for the position of the wear line are found so to obtain numerically an approximate solution. The model 1150^o C isotherm position profile are estimated by the vectors F(V) = (V1 ... VnV) as shown in Figure 4.2.
As a consequence, the Inverse problem of the estimation can be defined as the minimization of a function, represented by the equation 4.3:

$$F_{(V)} = \frac{1}{2} \sum_{i=1}^{nTermo} \left[T_{(X^{Termo}, V)} - T^{Termo} \right]^2 \qquad (4.3)$$

Where:Ttermo is the temperature registered by the thermocouples installed at the point X of the hearth; T(xTermo, V) is the temperature calculated by the finite elements technique using the V geometry for a particular position of the 1150^o C isotherm; X Termo is the position where one of the thermocouples is located.

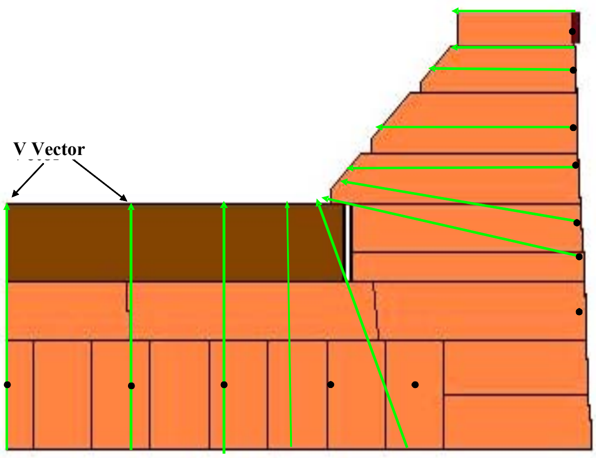


Figure 2: Hearth subdivision with the V vectors location.

The regulation chosen for this paper was based on the Gauss-Newton interactive method, the solution for which is represented by the equations 4.4 and 4.5:

$$V^{iter+1} = V^{iter} + \Delta V^{iter+1} \qquad (4.4)$$

$$\Delta V^{iter+1} = \left[DT^T \cdot DT + \alpha \cdot I\right]^{-1} \cdot \left[DT^T \cdot \Delta T_{V^{iter}} + \alpha \cdot I(V^{\Delta} - V^{iter})\right] \qquad (4.5)$$

Where Viter is the length of the vector for the interaction number determined; DT is the sensibility matrix; I is the identity matrix; ΔT(Piter) is the difference between the temperature measured by the thermocouples and the one calculated by the direct model; V^{Δ} is an *a priori* solution for the vector length admissible for the problem; α is the regulation parameter that represents a compromise between precision and stability.

For the α definition, the *a priori* regulation obtained from the Tikhonov regulation method where α = α(δ), δ, called noise level, is indicated by the equation 4.6, and α is obtained from the equation 4.7:

$$\delta \geq \left\| T^{real} - T^{termo} \right\|^2 \qquad (4.6)$$

$$\alpha = \delta^{\frac{2}{2\nu+1}} \qquad (4.7)$$

The sensibility matrix component is a partial derivation of the temperature in relation to the geometry. To obtain the matrix, it is necessary to carry out several simulations in the direct model, varying the V vetor. Basically, this matrix represents the temperature sensibility calculated by the model with the variation of each P vector position. The component VΔ represents a value that will be a reference for the solution. Because of the wear hearth characteristics, little evolution is expected. Therefore, we may use the model solution mentioned as the new reference.

4.4 Model Solution

The model solution is obtained by interaction. With the direct model, the temperature values at the thermocouples position are obtained for a wear profile, and the Inverse model determines the new position of the wear line minimizing the difference between the direct model temperature values and the values measured by the thermocouples.

The hearth wear assessment stages are described in the flowchart (Figure 3). The procedures are described for every stage.

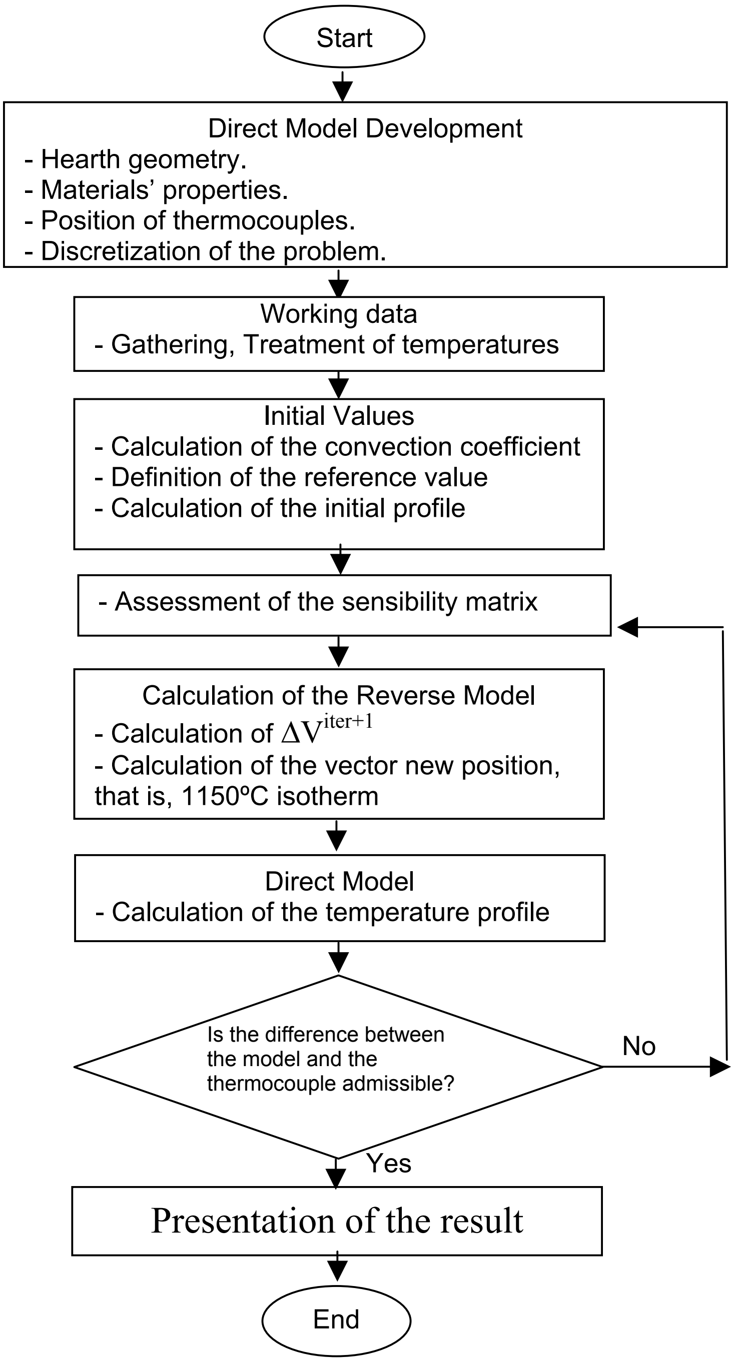


Figure 3: Flowchart of the wear assessment stages

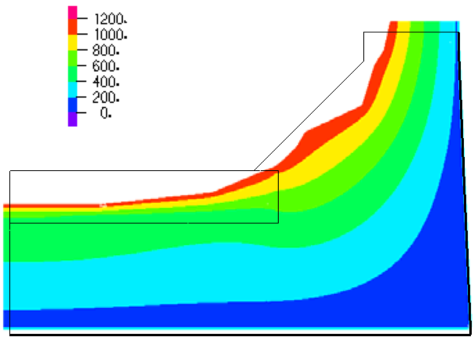
5 RESULTS AND DISCUSSIONS

The model for the hearth temperature distribution calculation aiming at assessing the wear level was applied in six different directions: iron notch 1, iron notch 2, iron notch 3, iron notch 4, 0^o position, and 180^o position. In order to verify the evolution, the temperatures from 1997 and 2005 were considered, because the temperature data from 1994 to 1996 were inconsistent.

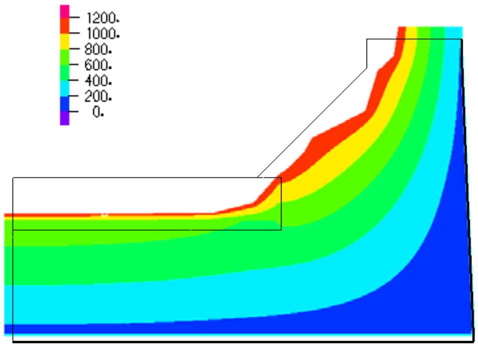
In order to validate the coherence, consistency, potencials, and flexibilities of the model, several hypotethical simulations were carried out so as to avoid big mistakes that could jeopardize the application. A sensibility assessment considering a 5% noise rate was carried out in order to validate the algorithm solution against possible noise in the wear assessment due to an error in the model data entered, such as thermal conductivity, convection coefficient, wear isotherm, and thermocouple measurement.

5.1 Wear Assessment

In order to present and apply the model, the results for the iron notch 2 direction are described below. The Figures 4 and 5 present the results from 1997, 1998, 1999, 2000, 2001, and 2002. It is possible to conclude that the bottom ceramic lining wear is already great in 1997. This result was expected, since the refractory is design to adjustment to the liquid passage profile. In the other periods, the base wear presents small variations without wearing out the carbon block, showing that the hearth bottom cooling is enough to form an aggregate layer. As to the wall, the wear profile was adjusted into a cup-shaped profile, as expected. The entire project was modifyed for the 1994 revamp to avoid wear to the “elephant foot” shape.

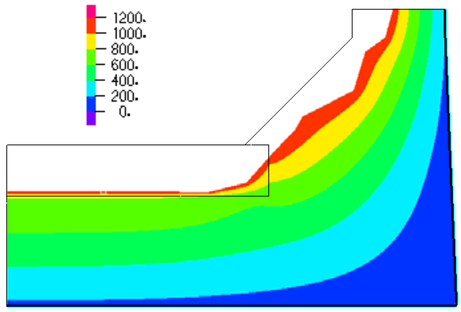


FG2 - 1997				
	Thermocouple	Model	ΔT	Error
B 34	309	309,5	-0,5	-0,2%
B 39	264	263,7	0,3	0,1%
B 40	187	187,3	-0,3	-0,2%
EL7790	67	66,5	0,5	0,7%
EL8350	77	82,1	-5,1	-6,6%
EL8700	94	97,3	-3,3	-3,6%
EL9300	97	139,8	-42,8	-44,1%
EL9700	163	162,9	0,1	0,0%
EL10300	160	190,1	-30,1	-18,8%
EL10700	202	203,6	-1,6	-0,8%

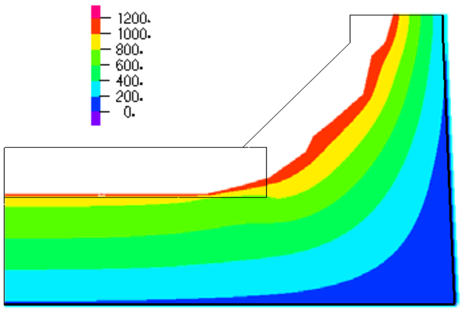


FG2 - 1998				
	Thermocouple	Model	ΔT	Error
B 34	376	376,3	-0,3	-0,1%
B 39	315	314,3	0,7	0,2%
B 40	199	199,4	-0,4	-0,2%
EL7790	68	68,2	-0,2	-0,3%
EL8350	76	84,1	-8,1	-10,6%
EL8700	97	99,6	-2,6	-2,7%
EL9300	99	143,6	-44,6	-45,0%
EL9700	169	168,5	0,5	0,3%
EL10300	165	200,9	-35,9	-21,7%
EL10700	218	218,0	0,0	0,0%

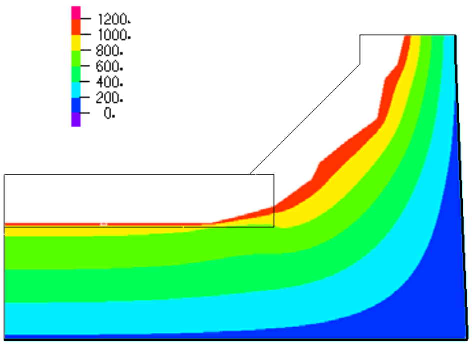
Figure 4: Tap hole 2 1997 and 1998 wear results



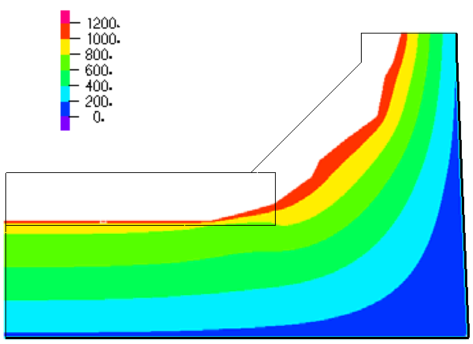
FG2 - 1999				
	Thermocouple	Model	ΔT	Error
B 34	423	420,9	2,1	0,5%
B 39	340	339,8	0,2	0,1%
B 40	199	198,0	1,0	0,5%
EL7790	66	66,6	-0,6	-0,9%
EL8350	78	81,1	-3,1	-4,0%
EL8700	95	95,4	-0,4	-0,4%
EL9300	103	137,1	-34,1	-33,1%
EL9700	162	163,5	-1,5	-0,9%
EL10300	159	205,9	-46,9	-29,5%
EL10700	231	231,6	-0,6	-0,3%



FG2 - 2000				
	Thermocouple	Model	ΔT	Error
B 34	422	422,5	-0,5	-0,1%
B 39	352	351,2	0,8	0,2%
B 40	233	232,0	1,0	0,4%
EL7790	74	74,8	-0,8	-1,1%
EL8350	84	92,7	-8,7	-10,3%
EL8700	105	109,9	-4,9	-4,7%
EL9300	121	157,9	-36,9	-30,5%
EL9700	184	184,1	-0,1	0,0%
EL10300	183	218,5	-35,5	-19,4%
EL10700	238	238,4	-0,4	-0,2%



FG2 - 2001				
	Thermocouple	Model	ΔT	Error
B 34	386	386,5	-0,5	-0,1%
B 39	346	346,3	-0,3	-0,1%
B 40	232	232,4	-0,4	-0,2%
EL7790	75	75,5	-0,5	-0,7%
EL8350	90	94,1	-4,1	-4,6%
EL8700	114	112,4	1,6	1,4%
EL9300	133	163,4	-30,4	-22,9%
EL9700	191	190,9	0,1	0,0%
EL10300	185	223,5	-38,5	-20,8%
EL10700	241	240,9	0,1	0,0%



FG2 - 2002				
	Thermocouple	Model	ΔT	Error
B 34	375	373,9	1,1	0,3%
B 39	338	339,3	-1,3	-0,4%
B 40	227	227,7	-0,7	-0,3%
EL7790	72	73,8	-1,8	-2,5%
EL8350	113	91,1	21,9	19,4%
EL8700	107	108,0	-1,0	-0,9%
EL9300	164	155,8	8,2	5,0%
EL9700	183	184,1	-1,1	-0,6%
EL10300	169	226,1	-57,1	-33,8%
EL10700	251	251,5	-0,5	-0,2%

Figure 5: Tap hole 2 1999 to 2002 wear results

5.2 Consolidation of results

Although the hearth project is simmetrical and the aim is to work with the same operational procedures, such as tapping time, tap hole length and others, the carbon blocks wear is not simmetrical. The Figure 6 presents the current wear results in all six directions, considering the temperatures measured up to the end of 2005. These results will be updated anually until the end of the campaign for comparison between the data measured after the campaign is finished and the model assessment. It is verified that the bottom region with less wear is the iron notch 2 region and the 180^{o} direction; the one which presented more wear is the iron notch 1 and the 0^{o} direction. Coincidentally, these are respectively the hearth bottom cooling inlet and outlet regions. This information allowed for the modification currently in progress of the cooling project for the 2009 revamp, which will allow for the bottom water flow change. As for the wall wear, the point where the thickness is smaller and that will probably determine the campaign ending is located in the iron notch 3. Work is already being executed in this iron notch in order to control the wear evolution.

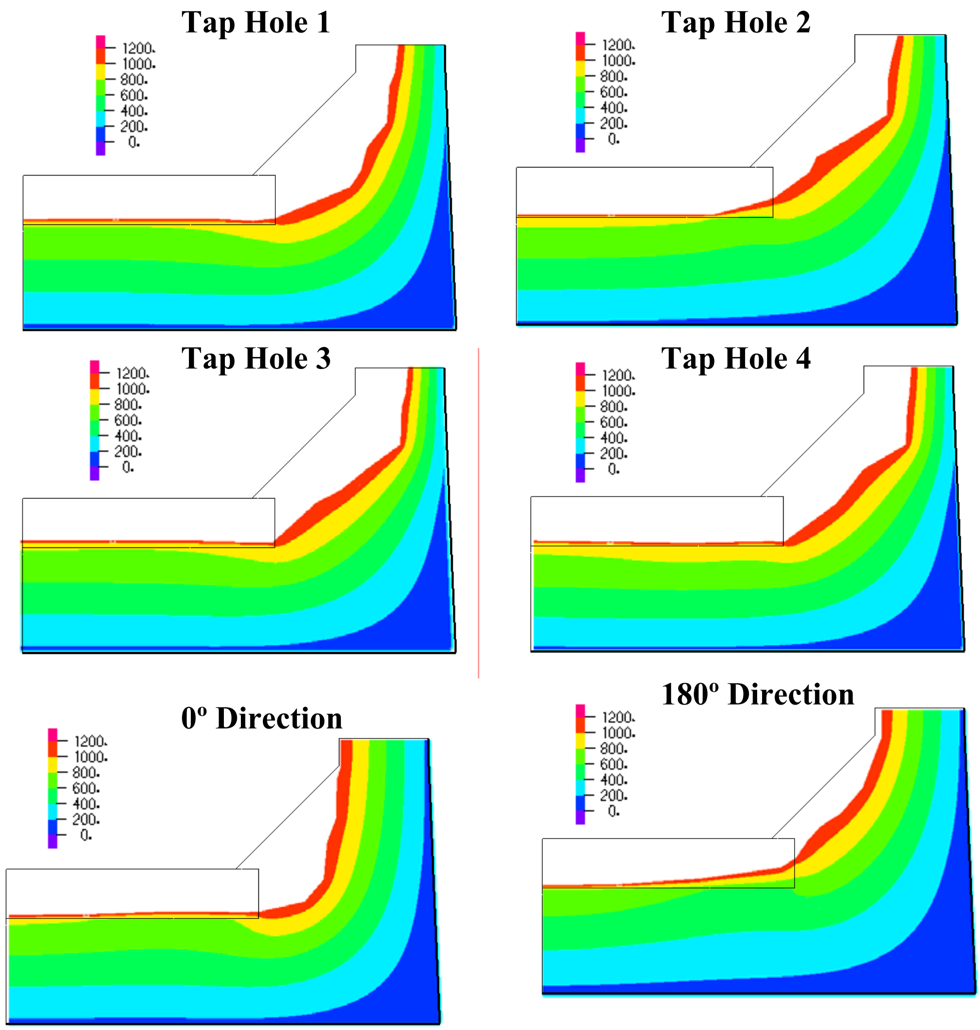


Figure 6 Current wear hearth profile.

6 CONCLUSION

Blast furnace monitoring with a model for assessment of the hearth wear during the blast furnaces operation is extremely important, especially by the end of the equipment's useful life, where attention to the safety of the operation, personnel, the environment, and the economic issues is higher because of the need to work with an accurate tool at the most appropriate moment to end the campaign. It also facilitates the improvement of the total blast furnace revamp planning.

The formulation of the model aimed at better results in terms of reliability and simplicity, by means of the transfer of the boundary conditions to the carbon blocks' external surfaces, setting fictional limits for the wall and bottom. These procedures help reduce the amount of data entered and the level of uncertainty, that is, it assists the determination of the thermal conductivity of the packed mass during the campaign evolution, and the convection coefficient due to the wall or hearth bottom water piping cooling films. Besides these procedures, the finite elements method and the Gauss-Newton regulation are strong numeric techniques valued for their level of accuracy and resources flexibility.
The model simulation results of the Gerdau Açominas blast furnace 1 hearth wear assessment have shown to be very coherent and a powerful tool for the purposes it was proposed.

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