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COMPARATIVE ANALYSIS OF BLAST FURNACE COOLER SYSTEM PERFORMANCE WITH DIFFERENT PRESERVATION TECHNIQUES AND DESIGN CONDITIONS

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Abstract. *Blast Furnace 2 of Ternium Brasil stellmaking company, in Rio de Janeiro, started to operate in December 16th, 2010. During its service life, the cast iron stave coolers displaced into the blast furnace and the copper stave coolers deformed, generating the lost of refrigeration capacity of these cooling system components. After the analysis was executed, several actions to recover and to preserve the Blast Furnace 2 were performed. This paper presents the evaluation of techniques used to maintain the stability of the equipment shell, emphasizing the aspects of fluid dynamics, maintenance methods and the thermal consequences in stave cooler bodies. To analyze the fluid performance and the outcomes in the stave coolers structure, a finite element computational fluid dynamics (CFD) model based on Ansys Fluent® was employed together with operational company datas, that permitted to estimate with good consistency and accuracy the flow characteristics. The main results of this research are the best procedures to stabilize the cooler system in good conditions without causing damages in the Blast Furnaces shell, and improvements in actual maintenance techniques to preserve the equipment and extend its service life.*

Keywords: *Blast Furnace, Stave Cooler, Fluid Dynamics, Computational Fluid Dynamics.*

1. INTRODUCTION

The Ternium Brasil stellmaking company, in Rio de Janeiro, operates two blast furnaces. These two equipments have the same production capacity and their operations started in 2010. The stack, belly and bosh cooler systems of the Blast Furnaces are stave coolers, and the hearths are jacket cooler (Maarten Geerdes and de Medeiros, 2009). The typical representation of blast furnace arrangement is shown in Fig. 1.

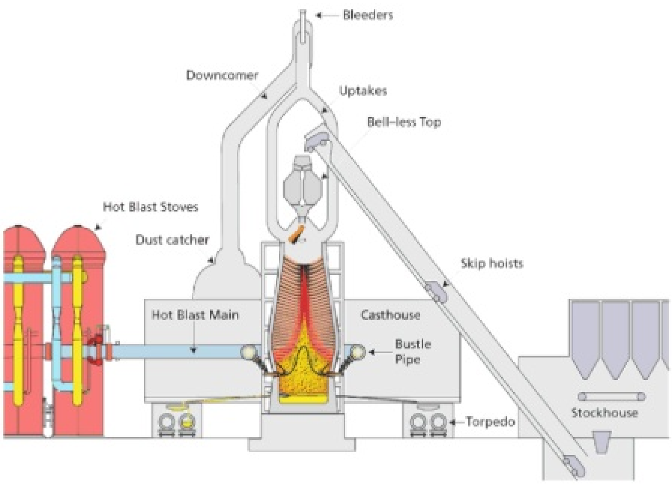

Figure 1. Example of blast furnace general arrangement, from Maarten Geerdes and de Medeiros (2009)

Several operational instabilities occurred in Blast Furnace 2, at the beginning of operation that were exarcebated by unprogrammed stoppages, so some undesirable consequences appeared. The main damages occured in components of cooler system, specifically in stave coolers that are installed into the blast furnaces. Thus, directions to preserve these components were established with the objective to restore the operational conditions and extend the service lives of the blast furnaces and the ancillary equipments. The technical information about the Blast Furnaces 2 of Ternium Brasil are shown in Tab. 1

Table 1. Main characteristics of Ternium Brasil Blast Furnace 2.

ITEM	UNIT	BF2
Internal volume	m^3	3284
Work volume	m^3	2775
Hearth diameter	m	12,0
Production capacity	t/day	7500
Quantity of tap holes	-	2
Quantity of tuyeres	-	32
Burden distribution type	-	Bell less top
Slag granulation type	-	INBA
Maximum blast temperature	°C	1250
Stack, belly and bosh cooler system	-	Stave coolers
Hearth coolers system	-	Jacket coolers
Start of service life	-	16/12/2010

The Ternium Brasil Blast Furnaces are equiped with cooper stave coolers disposed in four rows localized between the bosh and the inferior stack. The stave coolers, also disposed in four rows, localized between the medium stack and superior stack are made of cast iron. The Ternium stave coolers are equiped four parallel cooling lines, denoted as A,B,C and D. Line A is the first one on the left side and line D, the first one on the right side.

Many maintenance techniques are used to preserve the cooling capacity of staves coolers (Chung-ken Ho and hsiung Tung, 2013). Among these, the Ternium preservation team executes:

- Use alternative water in inverted flow until next programmed service to repair the cooling line;
- Repare the cooling line by welding process;
- Introduce flexible pipes into the damaged cooling lines;
- Insert cigar coolers to recover, partially, the stave cooler systems.

The present paper reports the evaluation of these preservation techniques regarding the fluid dynamics performance and the thermal consequences in the stave cooler bodies. Among them, the importance of knowing whether the stave coolers reach the mechanical limits of the materials employed in their fabrication. The main objective is to extend the blast furnace service life.

2. DOMAINS AND SOLUTION MODELS

2.1 Mathematical and numerical models

The fluid flow and the heat transfer processes occuring in the stave coolers were analyzed with a finite element computational fluid dynamics (CFD) model (see Ferziger and Peric, 2002), (see Donea and Huerta, 2003), (see Hughes, 1987). The governing equations of the problem are the continuity, Eq. (1), momentum, Eq. (2) and energy, Eq. (3) (Batchelor 2000, Pontes and Mangiavacchi 2016). :

$$\frac{\partial \rho}{\partial t} + \nabla \rho \cdot v = 0 \tag{1}$$

$$\frac{\partial v}{\partial t} + v \cdot \nabla v = -\frac{1}{\rho}\nabla p + \nu \cdot \nabla^2 v + g \tag{2}$$

$$\frac{\partial T}{\partial t} = \alpha \cdot \nabla^2 T + \frac{Q}{\rho \cdot C_v} \tag{3}$$

The method used to close and solve the problem is a turbulence viscosity model based in two transport equations: one transport differential equation to solve kinetic energy (κ) and one equation to solve the energy dissipation per mass unit (ϵ). This model is known as $\kappa - \epsilon$.

The $\kappa - \epsilon$ model represents the two equations model more used, and is currently considered the standard model for industry. It represents a suitable equilibrium between accuracy and robustness. The specific $\kappa - \epsilon$ choosed was the well known Standard Model (Átila P. Silva Freire and Colaço 2006).

The transport equation for κ can be obtained through Navier-Stokes equations. The equation for κ is represented in Eq. (4):

$$\frac{\partial \kappa}{\partial t} + \overline{u_j}\frac{\partial \kappa}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{\overline{p}}{\rho}u'_j + \frac{1}{2}\overline{\kappa u'_j} - \nu\frac{\partial \kappa}{\partial x_j}\right] - \overline{u'_i u_j}\frac{\partial \overline{u_i}}{\partial x_j} - \nu\overline{\left(\frac{\partial u'_i}{\partial x_j}\right)^2} \quad (4)$$

Terms on the left hand side of Eq. 4, represent the local variation rate and convective transport, and the terms into the square brackets are: difusive turbulent transport for the first and second term and molecular-difusive κ transport. And the penultimate term is production term that represents the energy transfer rate from average flow to turbulent flow.

The last term represents the conversion of kinetic energy in internal energy at the turbulent small scale. It also can be interpreted as viscous dissipation rate, represented per greek letter ϵ. The exact equation for viscous dissipation transport is represented in Eq. (5) also can be obtained through the Navier-Stokes equation (Átila P. Silva Freire and Colaço 2006).

$$\frac{\partial \epsilon}{\partial t} + \overline{u_j}\frac{\partial \epsilon}{\partial x_j} = P\epsilon + D\epsilon + d\epsilon \quad (5)$$

The terms $P\epsilon$,$D\epsilon$ and $d\epsilon$ represent the production, diffusion and destruction of ϵ, in analogy with the procedure adopted for κ. The exact equations contain a large number of variables and double correlation between velocity fluctuation and velocity/pressure fluctuation gradients (see Átila P. Silva Freire and Colaço, 2006). Due to the dificulty of obtaining the exact description of these terms, they are modeled using dimensional analysis techniques and interpretation of physical process involved. The application of hyphotesis and aproximations cited above creates the standard formulation $\kappa - \epsilon$ for high Reynolds coefficients represented in Eq. (6) and Eq. (7). The turbulent viscosity is defined per Eq. (8).

$$\frac{\partial \kappa}{\partial t} + \overline{u_j}\frac{\partial \kappa}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\nu\frac{\nu_t}{\sigma_\kappa}\right)\frac{\partial \kappa}{\partial x_i}\right] + \left[\nu_t\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \frac{2}{3}\kappa\delta_{ij}\right] - \epsilon \quad (6)$$

$$\frac{\partial \epsilon}{\partial t} + \overline{u_j}\frac{\partial \epsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\nu\frac{\nu_t}{\sigma_\epsilon}\right)\frac{\partial \kappa\epsilon}{\partial x_i}\right] + C_{\epsilon 1}\frac{\epsilon}{\kappa}\left[\nu_t\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \frac{2}{3}\kappa\delta_{ij}\right]\frac{\partial \overline{u_i}}{\partial x_j} - C_{\epsilon 2}\frac{\epsilon^2}{\kappa} \quad (7)$$

$$\nu_t = C_\mu\frac{\kappa^2}{\epsilon} \quad (8)$$

The values of constants C_μ, σ_κ, σ_ϵ, $C_{\epsilon 1}$ and $C_{\epsilon 2}$, in the standard formulation of model $\kappa - \epsilon$, are obtained from correlations of several turbulent experimental data. The values are presented in the Tab. 2.

Table 2. Contant values for standard turbulent model $\kappa - \epsilon$

CONSTANTS	VALUES
C_μ	0.09
σ_ϵ	1.30
σ_κ	1.00
$C_{\epsilon 1}$	1.44
$C_{\epsilon 2}$	1.92

The fluctuation of the velocity components along with κ result in the existence of calm regions, which finally build large velocity and κ gradients. This situation is induced by the turbulent flow approaching the interface. The high turbulence stresses away from the wall decrease for the layer near the wall for values close to the viscous stresses. Describing the flow in these regions require a sufficiently smooth numerical mesh that result in high computational costs for low Reynolds numbers. In the other extreme, for high Reynolds numbers, it is not necessary to solve the flow close to the wall.

In consequence, a restricted use of wall functions can be adopted, reducing the computational costs. Scalable wall functions were presently chosen, since high Reynolds numbers are involved and a description of the turbulent motion in the boundary layer is not sought. This is the situation presently addressed. As a result, good accuracy is obtained when an innertial first sublayer exist at normalized distances (Moukalled Fadl and Marwan, 2016).

2.2 Process data: acquisition, treatment and analysis of influence

The specific data affecting the performance of Staves Coolers were choosed using the techniques of brainstorming and priority matrix (Wortman *et al.*, 2012) with the Ternium blast furnace technical specialists. The list of selected data is:

- Soft water temperature in inlet (°C);
- Surround temperature(°C);
- Soft water velocity in cooler lines (m/s);
- Soft water specific mass (kg/m^3);
- Soft water viscosity (N.s/m^2);
- Soft water thermal condutivity (W/m.K);
- Soft water heat transfer coefficient (W/m^2.K);
- Cooper and cast iron stave cooler pipes heat transfer coefficient (W/m^2.K);
- Cooper and cast iron thermal condutivity (W/m.K);
- Cooper and cast iron specific heat (J/kg.K);
- Effective cold face heat transfer coefficient (W/m^2.K);
- Hot face thermal flux in cooper and cast iron staves and cigar coolers (W/m^2).

Data acquisition of Ternium Blast Furnace Cooler System is made using the PIMS (Plant Information Manegement System) software by OSISoft ® . The software collects and performs the preliminar treatment of the information, from the equipment start up to present date. The acquired data were used to create a Design of Experiment Factorial to analyze the influence of uncorrelated and of correlated plant production parameters, in the Staves Coolers performance. Another data are choosed to analyze in special situation as cigar coolers, flexible hoses or alternative water use.

The data were analyzed using the factorial design of experiment technique (DOE) (see D.Montgomery and G.Runger, 2011), which is fed to the Minitab ® software. The output parameter choosed for DOE is the temperature in a specific region of stave coolers hot face, this point is called *Tpto45*. The results of this technique are presented in Fig. 2 and Fig. 3 that show the significance of variables: heat loss, inlet soft water temperature, soft water viscosity, soft water velocity and some coupled variables. .

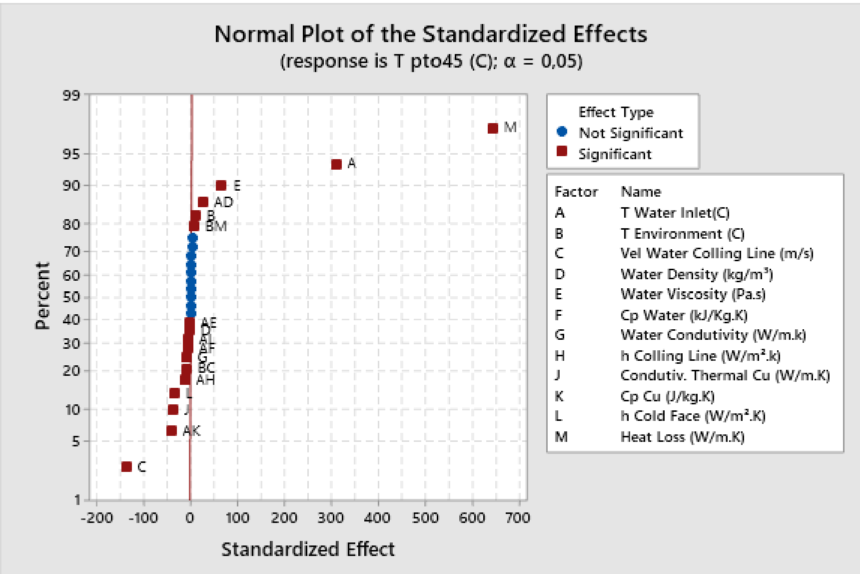

Figure 2. Normal Plot of standardized effects

Figure 4 presents the standardized residuals performance, showing residuals with random distribution relative to fitted values, the normal distribution without presence of outliers, and a plot showing that residuals ara not correlated with the sampling sequence. These evidences show that the parameters can affect the results of the variable *Tpto45*. These observations lead to the conclusion that the effect of the choosed parameters are significant, and all parameters are evaluated in the solution process.

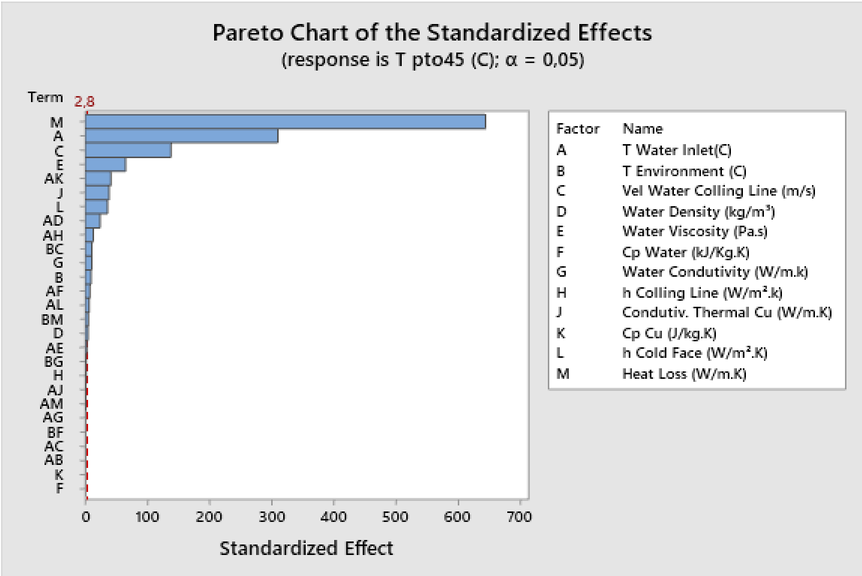

Figure 3. Pareto Chart of standardized effects

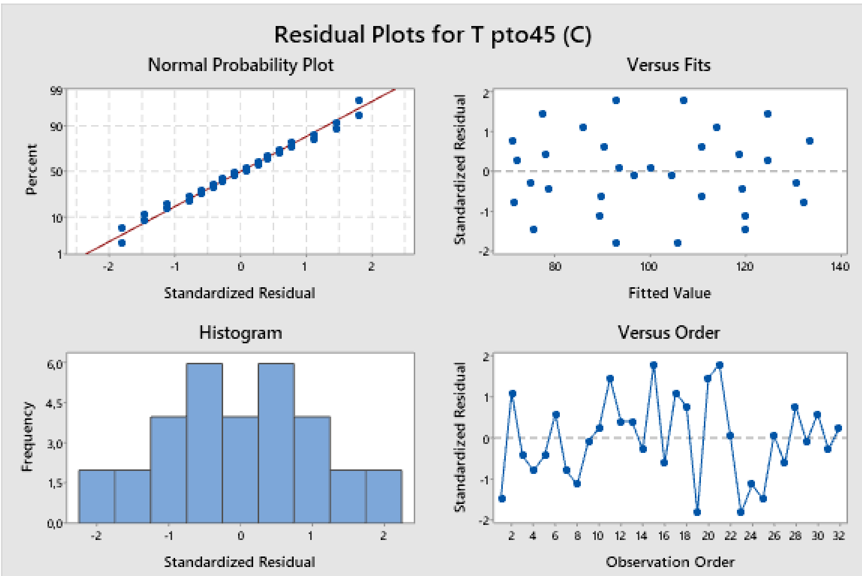

Figure 4. Residuals plot for specific point

2.3 Domain selection

The stave cooler body is the domain to study the performance and consequences of maintenance or preservation techniques. The dimensions and main characteristics of stave coolers are the same of Ternium design. The solid geometry of domain is made by Ansys SCDM ® and the Fig. 5 represents the cooper stave cooler geometry.

The stave cooler domain changes when the actions to restore and preserve blast furnaces are executed. Welding repairs restore the stave coolers original condition, and at the same time, do not result in changes that affect the original fluid flow configuration. Repairs with flexible hoses with smaller diameters and different roughness, inserted in cooling lines, do change flow conditions. However the simulations present in this paper suggest that the flow is not significantly affected by the flexible hoses roughness. Stave cooler repairs using cigar coolers do change the configuration of the cooling lines, by blocking lines with refractory mass. The flow becomes perpendicular to the original one. Figure 6 schematically shows the details of cigar coolers. Figure 7 shows the preliminar configuration of the repair.

The numerical simulations presentd in this paper were performed in meshes internally generated by the Ansys Fluent ®, following the steps defined for its instructions (Ansys, 2020). The mesh quality was checked before performing the simulations. The prescribed mesh quality parameters are skewness (< 0,80) and minimum orthogonal quality (> 0,15) according to the instructions of the software user guide.

The main parameters adopted for solving the flow and temperature fields are:

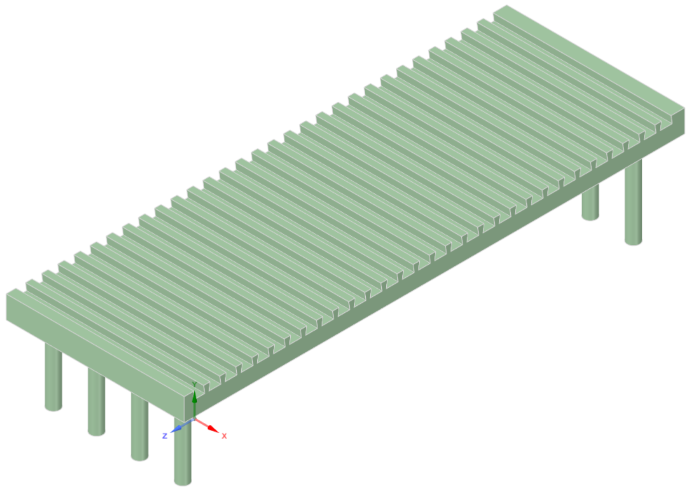

Figure 5. Example of solid geometry domain

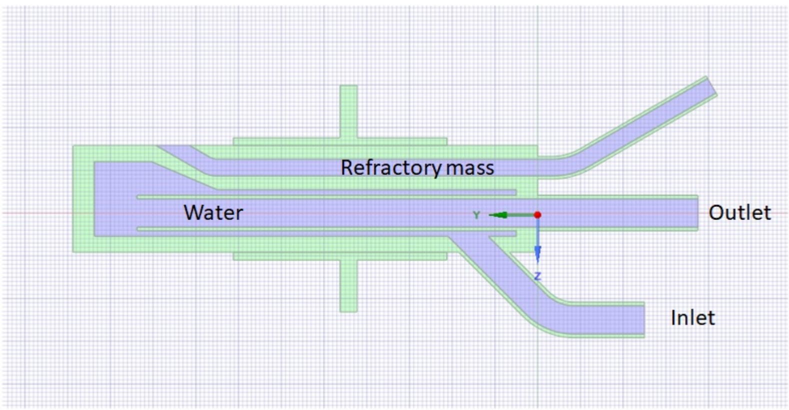

Figure 6. Cigar cooler details

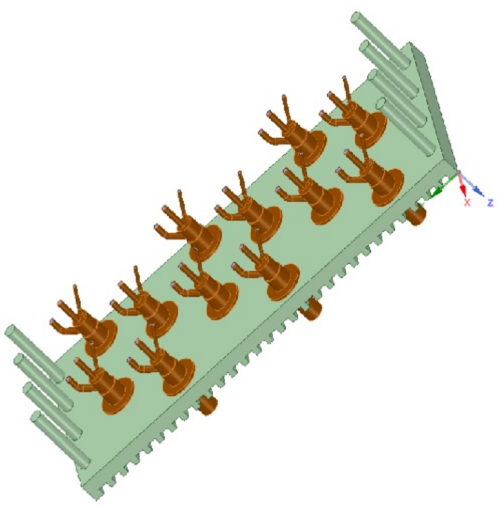

Figure 7. Stave Cooler with cigar coolers installed

- Material properties (specific mass, specific heat, thermal condutivity, viscosity,..) for cooper, cast iron, steel, refractories and water;
- Boundaries conditions: Inlet velocity and pressure outlet (the robustness is favoured), interface regions and wall conditions;
- Selection of the variables to include in the report definitions to control convergence of the solution. The selected variables are flow rate, velocity and pressure at outlets and also the temperature at inlets.

Values of the materials properties and selection of boundary conditions were made in accord with the results of the variable temperature *Tpto45* in DOE. The critical conditions of this response variable represents the worst situation that the stave cooler is subject and the normal conditions represents the ideal operation condition of the stave coolers. The values of variables and parameters for computational estimative are presented in Tab. 3.

Table 3. Data for numerical simulation

PROPERTIES AND PARAMETERS	*Tpto45* Normal conditions	*Tpto45* Critical conditions
Inlet water temperature in copper staves (°C)	41.5	58.5
Inlet water velocity in copper staves (m/s)	1.95	1.50
Surround temperature (°C)	50	50
Water specific mass (kg/m^3)	982,34	989,84
Water viscosity (N.s /m^2)	6,442 x 10^{-04}	8,382 x 10^{-04}
Water thermal condutivity (W/m.K)	0,645	0,627
Heat transfer coefficient in cooper stave pipes (W/m.K)	8117,7	8117,7
Cooper thermal condutivity (W/m.K)	409,90	409,90
Copper heat Specific (J/ kg.K)	429,75	362,57
Cast iron thermal condutivity (W/m.K)	35,90	59,67
Effective cold face heat transfer coefficient (W/m^2.K)	9,77	9,77
Cooper Staves hot face thermal flux (W/m)	33078,9	67262,7
Inlet water temperature in cast iron staves (°C)	43,6	53,1
Inlet water velocity in cast iron staves (m/s)	1.48	1.29
Heat transfer coefficient in cast iron stave pipes (W/m.K)	5948,0	5948,0
Cast iron heat specific (J/ kg.K)	903,74	464,57
Cast iron Stave hot face thermal flux (W/m)	12319.5	26540,0
Cigar cooler hot face thermal flux (W/m)	127856,2	259983,3
Heat transfer coefficient in cigar cooler pipes (W/m.K)	588,7	588,7
Inlet water velocity in cigar cooler pipe (m/s)	4,10	2,28
Outlet water velocity in cigar cooler pipe (m/s)	0,067	0,037
Inlet no pressure water velocity (m/s)	0,39	0,22
Inlet water velocity in flexible hoses (m/s)	2,81	1,56
Heat transfer coefficient in flexible hoses (W/m.K)	13243.9	13243.9

3. COMPUTATIONAL RESULTS AND DISCUSSION

The results of stave cooler performance, reached in numerical simulation put in evidence the best way to operate and repair the stave coolers damaged. Some examples for these situations are presented in Fig. 8, Fig. 9 and Fig. 10.

Cooper materials when exposed to high temperature present strenght tensile and yield stress decrease in elevate rate due to the grain size increase (ASM, 1990), as represented in Fig. 11. The phenomena in cooper materials, known as softening in temperatures close to 370°C, corresponds to abrupt decreases in these properties. Similar change in performance is observed with cast iron materials, due to grain size increases. However, the change in this material occurs at higher temperatures, close to 500°C, since the cast iron thermal condutivity is lower than the one of the cooper. The temperatures for operational control are: 150°C for cooper staves and 350°C for cast iron staves, which are lower than the material limits due to the operation safety requirements.

Based on the analysis of the temperature contours, we can draw conclusions about the performance of stave coolers that received maintenance actions. The most important conclusion, as seen Fig. 8, Fig. 9 and Fig. 10, is that the staves can not stay without cooling fluid for long time, since this procedure can result in severe damages in the stave bodies. These damages can bring serious problems with the structure stability of the blast furnace shell. Some conditions for operation should be avoid, having in mind deformations in stave coolers and future damages that can occur in these

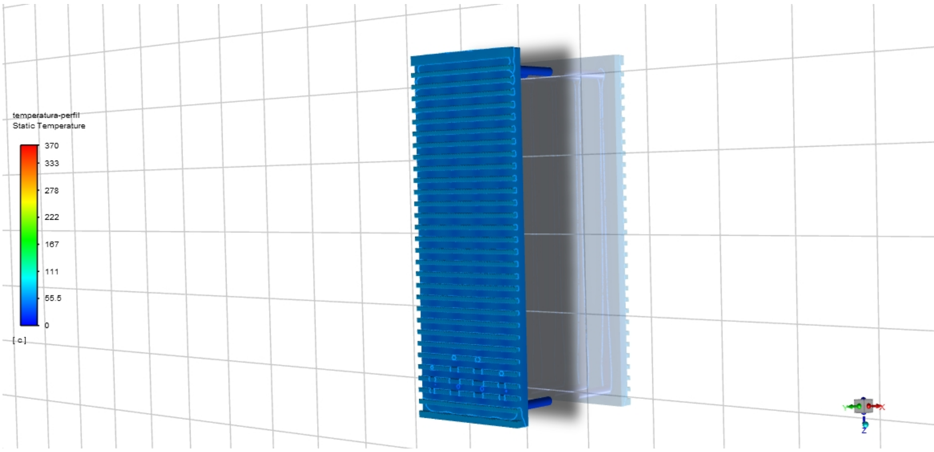

Figure 8. Stave cooler original in normal operation conditions

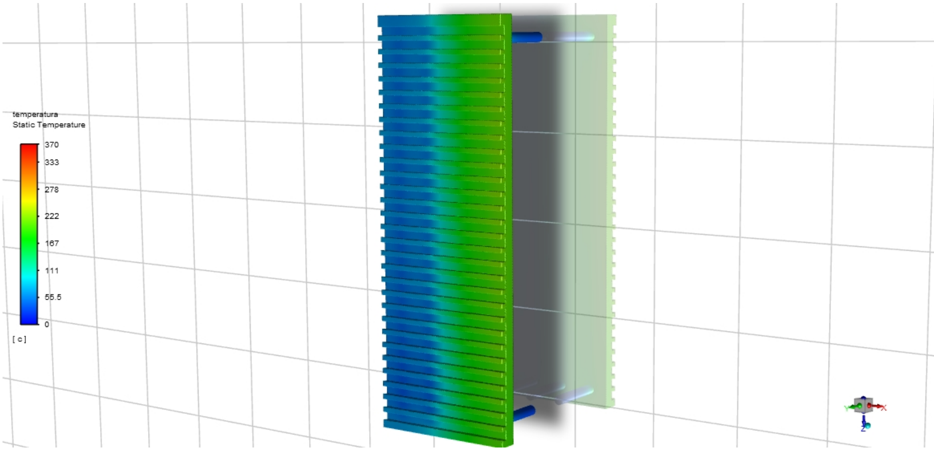

Figure 9. Stave cooler with flexible hoses in lines A and B in normal poeration conditions

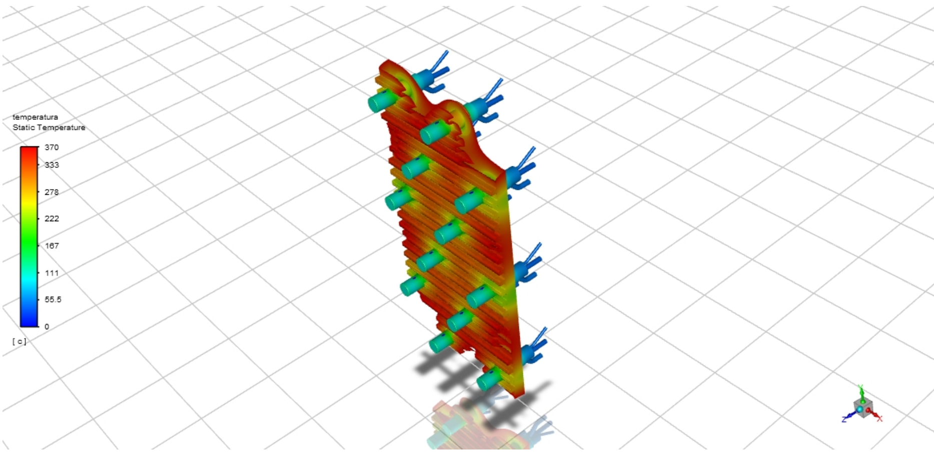

Figure 10. Stave cooler with cigar coolers in critical operation conditions

components. The situations are listed in Tab. 4: flexible hoses $\oslash 1$" (lines A,B) - cooper stave - critical conditions; flexible hoses $\oslash 1/2$" - 4 lines- cooper stave - normal conditions; flexible hoses $\oslash 3/4$" - 4 lines- cooper stave - critical conditions; blocked refractory mass (line A) - cooper stave - critical conditions; blocked refractory mass (lines A,B) - cooper stave - normal conditions and stave with 12 cigar coolers - cooper stave - critical conditions must be avoided since the stave coolers are operating beyond the upper thermal and mechanical material limits.

The other conditions are not of interest, since the stave mechanical properties deteriorate above 200 °C, what result in future maintenance issues of these components: original cooper stave - critical conditions; alternative water (line A) cooper stave - critical conditions; flexible hoses $\oslash 3/4$" (line A) - cooper stave - normal conditions; flexible hoses $\oslash 3/4$" (lines A,B) - cooper stave - normal conditions; flexible hoses $\oslash 1$" - 4 lines- cooper stave - normal conditions; blocked

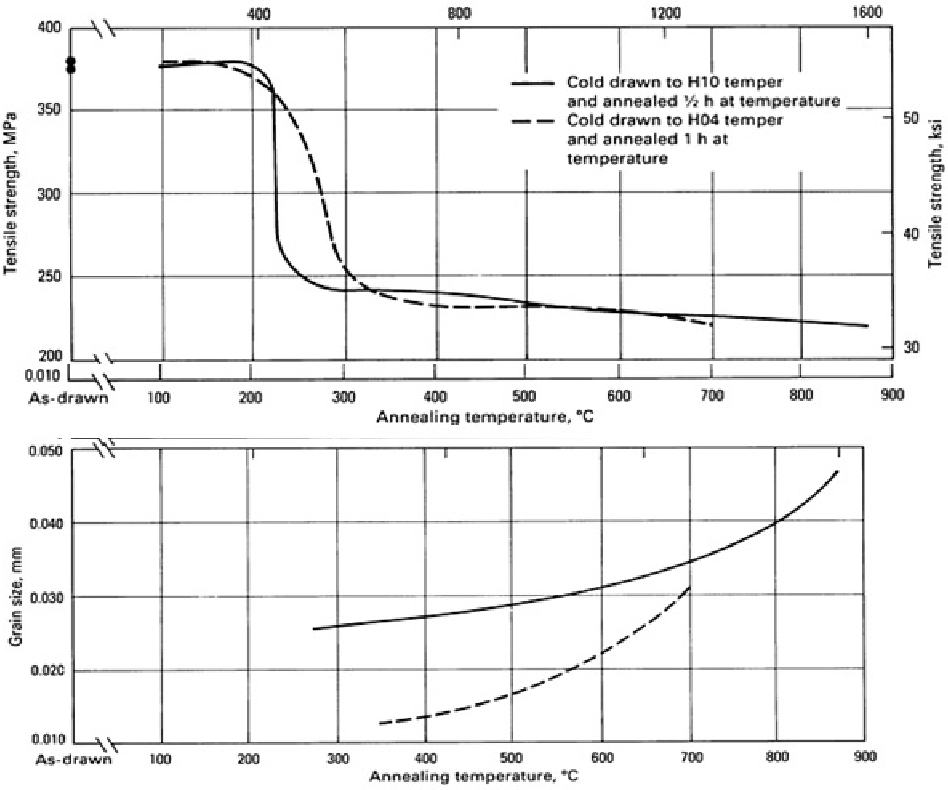

Figure 11. Cooper material mechanical performance versus temperature (ASM, 1990)

Table 4. Results of staves cooler performance

SITUATION ANALYZED	MAXIMUM TEMPERATURE (°C)
Original cooper stave - Normal conditions	88
Original cooper stave - Critical conditions	222
Alternative water (Line A) cooper stave - Normal conditions	110
Alternative water (Line A) Cooper stave - Critical conditions	270
Flexible hoses ⌀1" (Line A) - Cooper stave - Normal conditions	139
Flexible hoses ⌀1" (Line A) - Cooper stave - Critical conditions	337
Flexible hoses ⌀3/4" (Line A) - Cooper stave - Normal conditions	229
Flexible hoses ⌀3/4" (Line B) - Cooper stave - Normal conditions	144
Flexible hoses ⌀3/4" (Lines A,B) - Cooper stave - Normal conditions	250
Flexible hoses ⌀1" (Lines A,B) - Cooper stave - Normal conditions	238
Flexible hoses ⌀1" (Lines A,B) - Cooper stave - Critical conditions	> 400
Flexible hoses ⌀3/4"- 4 lines- Cooper stave - Normal conditions	300
Flexible hoses ⌀1" - 4 lines- Cooper stave - Normal conditions	240
Flexible hoses ⌀1/2"- 4 lines- Cooper stave - Normal conditions	> 400
Flexible hoses ⌀3/4" - 4 lines- Cooper stave - Critical conditions	> 400
Blocked refractory mass (line A) - Cooper stave - Normal conditions	240
Blocked refractory mass (line A) - Cooper stave - Critical conditions	> 400
Blocked refractory mass (line B) - Cooper stave - Normal conditions	147
Blocked refractory mass (line B) - Cooper stave - Critical conditions	280
Blocked refractory mass (lines A,B) - Cooper stave - Normal conditions	> 400
Stave with 12 cigar coolers - Cooper stave - Normal conditions	332
Stave with 12 cigar coolers - Cooper Stave - Critical conditions	> 400
Original cast iron stave - Normal conditions	203
Original cast iron stave - Critical conditions	267

refractory mass (line A) - cooper stave - normal conditions; blocked refractory mass (line B) - cooper stave - critical conditions.

The desired or acceptabe situations to operate the blast furnace in relation with the staves cooler are: original cooper stave - normal conditions; alternative water (line A) cooper stave - normal conditions; flexible hoses ⌀1” (line A) - cooper stave - normal conditions; blocked refractory mass (line B) - cooper stave - normal conditions. Is important to point that the blast furnace operation conditions should be stable to avoid disturbances close to the stave coolers hot face, that lead to major damages in these components.

Suggestions for future works include a performance analysis of the blast furnace shell conjugated with the original stave coolers or with the maintenance actions to preserve these components, as well as other possible configurations with cigar coolers, flexible hoses or alternative water that improve the cooling capacity and do not create hot spots on the shell.

4. ACKNOWLEDGEMENTS

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