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Implementation of convective heating in Companhia Siderúrgica Nacional Blast Furnace runners

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HIGHLIGHTS

► We describe the main advantages of heating convective system of refractory lining.
► We developed a ceramic coating to protect the refractory lining against oxidation.
► We increase the availability of Blast-furnace Runners and reduce the natural gas consumption.

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ABSTRACT

This paper describes the main characteristics and advantages of convective heating system for refractory lining, compared with conventional heating systems. In addition the main results obtained are presented with its implementation in CSN Blast Furnace #2 and 3 Runners, in terms of cost and equipment availability, as well as the need for ceramic coating to protect the lining against oxidation, arising from excessive air combustion.

1. Introduction

The drying of water-containing ceramic materials, is complex process. Ultra Low Cement Castable (ULCC) has around 5 mass-% water, and excessive heat-up can cause explosive spalling if dried improperly [1].

Refractory linings, like the blast furnaces runners, are generally composed of multiple layers of varying insulating materials and a dense abrasion resistant hot face layer. According to Palmer, for steady conditions, in a flat or thin layer, the conduction heat flow, Q, through each layer is well defined by, Eq. (1) [2]:

$$Q = k/\Delta x \cdot A \cdot \Delta T \qquad (1)$$

where, k is average thermal conductivity of the layer material, Δx its thickness, A its heat-transfer area and ΔT the temperature difference across the layer.

The heat transport required to supply the energy to heat up the overall system, Q, is the sum of the variables q_1, q_2 and q_3. Eq. (2) describes the heating of water (q_1), Eq. (3) describes the evaporation of water (q_2) and Eq. (4) describes the heating of the castable (q_3) [1]:

$$q_1 = h_0 \cdot \rho_w \cdot c_{pw} \cdot v \qquad (2)$$

$$q_2 = h_0 \cdot \rho_w \cdot H_w \qquad (3)$$

$$q_3 = \rho_{FF} \cdot C_{pFF} \cdot v \qquad (4)$$

where h_0 is the initial content of water [kg/kg], ρ_w is water's specific weight [kg/m^3], c_{pw} its specific heat [kJ/kg K], H_w its heat of evaporation [kJ/kg], C_{pFF} the specific heat of castable [kJ/kg K] and q_1, q_2 and q_3 are given in kJ/m^3. Eq. (5) shows the resulting heat flow:

$$\dot{Q} = \alpha(v_L - v_0) = \frac{\lambda_{FF}}{S_{dr}}(v_0 - v_k) \qquad (5)$$

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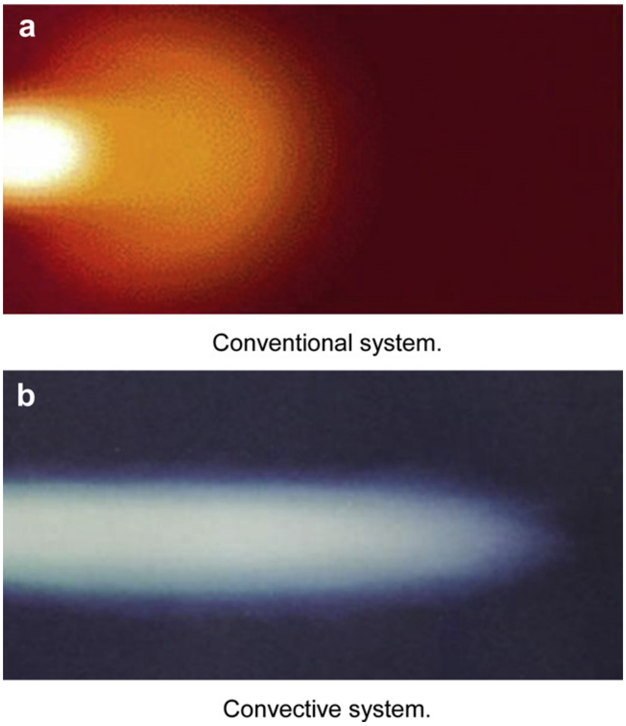

Fig. 1. Comparison of heating system flame profiles.

where α is the heat flow coefficient [W/m^2 K], $(v_L - v_0)$ is the temperature difference between the surface at the beginning (v_L) and the surface of castable after heating, $(v_0 - v_k)$ is the temperature difference between the surface of castable at the beginning and the drying plane, λ_{FF} is the thermal conductivity of the refractory castable [kW/m K] and S_{dr} is the thickness of the already dried layer [m]. Pötscvheke's results prove that the evaporation process is not determined by mass transport, but depends rather on the proper control of temperatures increase during the refractory castables drying process [1].

The system applied to heat up the blast furnace runners provides high convective heat transfer. The equipment is mainly compound of one turbo-blower and one burner, both working in convective regime. This is due to the velocity of pre-heated air injection, which can reach up to 150 m/s. Besides, this operation regime gives a high control of the incremental temperature, and can follow securely the programmed heating curve, with high precision, preventing structural spalling of castable that occurs when the liquid water still present beyond the drying plane suddenly evaporates [1]. Hence, the overall time of operation is considerably reduced, enabling the equipment to operation and therefore, decreasing the overall cost of the process. This type of heating also guarantees homogeneity in the temperature distribution, which is critical to assure the performance of the refractory layer during operation.

Table 1
Comparison between conventional and convective heating systems.

Characteristics	Heating system	
	Convective	Conventional
1. Transfer mechanism of prevalent heat.	Convection	Radiation
2. Heat distribution.	Homogeneous	Heterogeneous
3. Controllability.	High (room temperature at 1370 °C)	Low (per zones)
4. Excessive air.	3300%	Up to 100%
5. Burner.	High speed	Low speed (process)
6. Pressure.	Positive	Negative to neutral
7. Fuel.	Gas or gas + liquid	Just one fuel
8. Flame stability.	High	Low
9. Safety devices.	Double	Single or unavailable
10. Portability.	Movable	Fixed

Table 2
Natural gas consumption at Blast Furnaces #2 and 3.

Month	BF #2 [dam^3]	BF #3 [dam^3]	PCI [dam^3]	Total [dam^3]	BF #2 [%]	BF #3 [%]	PCI [%]
Jan	719	719	65	1503	48	48	4
Feb	671	671	61	1403	48	48	4
Mar	719	719	65	1503	48	48	4
Apr	699	699	64	1562	48	48	4

In recent years, there has been much discussion on the nature of complexity in physical systems, and many researchers believe that a new science needed to be created to fully study this area [3]. In general, ideas have broad applicability, but their use requires care and good judgment. Simulations with a large eddy demonstrate that the splatting and antisplatting events play an important role for the turbulent energy transfer between the vertical and the free surface parallel directions. Therefore, the vortices contribute to surface renewal at free surface, help control heat transfer and induce anisotropic turbulent flow near the free surface [4].

The Thermojet burners applied to runner, according to Kreith, are classified as free single submerged jets, where the flow is affected by the surface shear stress [5]. This results in a drag of significant parcel of the fluid by the jet. The dragged fluid affects the flow and its initial characteristics. Therefore, the fluid becomes thicker in the flow's direction [5]. The runner's geometry can be associated to the parallel plates theory. In such a system the Reynold's number can get values around 5×10^5 [6].

In conventional heating, the heat transfer occurs principally by the absorption of infra-red radiation. The heat flux, q_{rad}, stated as in Eq. (6):

$$q_{rad} = h_r \cdot (T_s - T_r) \tag{6}$$

where, T_s is the temperature in the burner [°C], T_r is the temperature in the refractory lining [°C], h_r is the heat flow coefficient [W/m^2 K].

The latter is a function of temperature variation, and can reach significant values when temperatures overcome 700 °C. This value was obtained by in situ experience in some industries. The magnitude of this coefficient is inversely proportional to the square of the distance between the flame and the refractory lining [5]. The rate of heat transfer by convection (q_{conv}) follows Newton's law, Eq. (7) [5].

$$q_{conv} = h \cdot A_s (T_s - T_\infty) \tag{7}$$

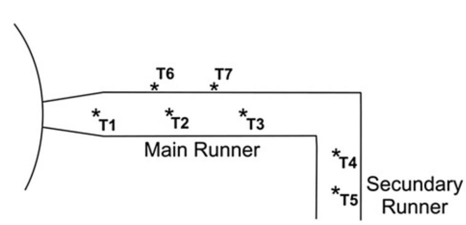

Fig. 2. Thermocouple location of BF #3 Runners.

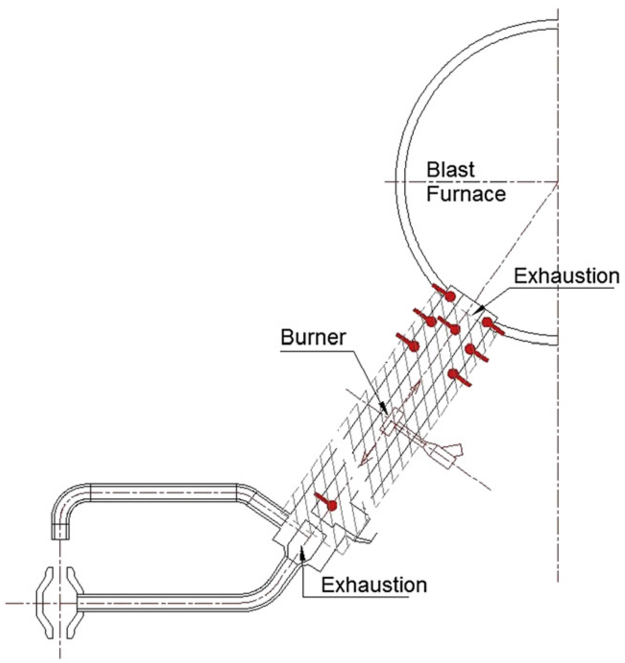

Fig. 3. Top view of the burner.

where A_s is the heat transfer area [m^2], T_s is the interface temperature [°C] and T_∞ is the temperature in the fluid closer of interface [°C].

The efficient of the heating depends of the convective heat flow coefficient value, h_{conv}, and this coefficient is proportional to Reynold's number elevated to 4/5, getting high efficient in the heat transfer in turbulent flux [7]. Until about 400 °C, the flame of the burner keeps into the burner's pipe, and the heat transfers occur only by forced convection.

Drying is a fundamental problem involving simultaneous heat and mass transfer under transient conditions resulting in a system of coupled nonlinear partial differential equations. A number of internal and external parameters influence drying behaviors. External parameters include temperature, velocity and relative humidity of the drying medium (air), while internal parameters include density, permeability, porosity, sorption-desorption characteristics and thermo physical properties of the material being dried [8].

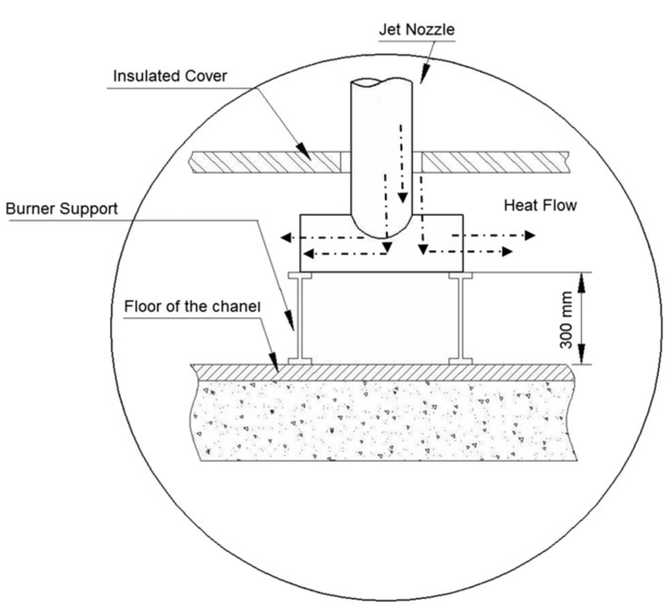

Fig. 4. Illustration of the burner positioned into the Blast Furnace Runner.

Fig. 5. The heat-up processes of CSN BF #2 Runners.

Table 3
Natural gas consumption measured at Blast Furnaces #2.

Equipment	Time [h]	Consumption [m^3]
Main runners		
MR #1	8	80
MR #1	15	224
MR #2	15	155
MR #2	7	58
Tap hole bonnets		
TP #2	12	82
TP #1	8	
Annual consumption		*3398*
Average consumption/month		*283*

The drying porous media has been studied by several investigators [9–11]. In case of castable with high fraction of closed porous, it is necessary to apply one most controlled heat curve to prevent structural spalling. The process has the following primary purposes [12]:

a) Remove in a controlled way the free water – not chemically bonded; vaporization rate peak occurs at 150 °C;
b) Remove in a controlled way the chemically bonded water; the crystallization water in the hydrated phases is eliminated in

Table 4
Natural gas consumption measured at Blast Furnaces #3.

Equipment	Time [h]	Consumption [m^3]
Main runners		
MR #1	48	1176
MR #3	36	1257
MR #1/Secondary R	24	824
MR #4	48	1261
MR #2	47	1241
MR #1/Secondary R	48	1783
MR #3/Secondary R	48	1781
Tap hole bonnet		
TP #1	14	114
TP #3	14	114
Annual consumption		*4022*
Average consumption/month		*335*

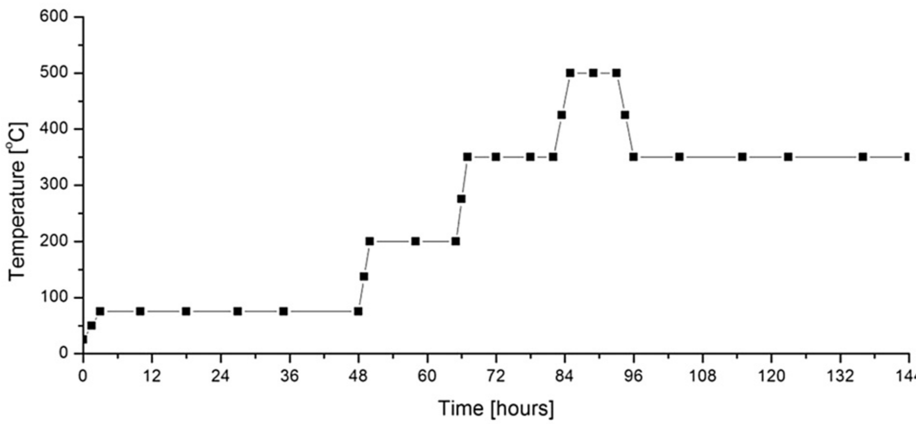

Fig. 6. Conventional drying/heating curve of BF #3 Runners.

a gradual way at different temperatures for each hydrate. The dehydration process ranges from 200 to 600 °C, however the bulk of water is eliminated up to 350 °C.

c) Ensure lining soundness; running at uniform heating rates mitigates temperature gradients over the lining, thus reducing explosion risks.
d) Increment material properties; an appropriate drying/heating curve results in lining better performance, which requires less maintenance while upping equipment availability.
e) Reduce the risks involving equipment operational resumption.

The drying/heating curve may be controlled by means of thermocouples inserted in the lining itself and/or thermocouples installed on the equipment metal shell. Care should also be taken regarding equipment apertures and exhaustions, so that the equipment may be kept pressurized. Moisture and dew point measurements at the exit may also be required.

The amount of heat which is transferred to the lining, Q_{cond}, by the heating system is the same as the sum of heat transferred by convection, Q_{conv}, and the amount of heat transferred by radiation, Q_{rad}, Eq. (8).

$$Q_{cond} = Q_{conv} + Q_{rad} \tag{8}$$

Up to about 700 °C, heat transfer by convection is a great deal more efficient. That's why convective heating technology becomes quite an interesting alternative. The conventional drying/heating system is characterized by the installation of gas nozzles in a depressurized environment. The shortcomings of this system include:

a) Direct flame on refractory lining, with temperatures above 1500 °C, which adversely affects the material leading to hot spots and lining oxidation. Runner refractory castable has carbon, C, in granulated pitch form, and silicon carbide, SiC, which are oxidized above 450 °C and 900 °C, respectively.
b) Heat penetration in the lining is not uniform, with very high temperatures next to the gas nozzles, and very low temperatures as the distance from the aforesaid gas nozzles becomes farther. In case of chemically bonded products, which require a minimum temperature to trigger ignition reactions, this may be a disastrous situation.
c) It is not possible to pressurize the environment, lifting temperature gradients over the lining, which may lead to crack dissemination and, in a worst case scenario, cause explosions as a result of high amounts of released steam at localized points.

The main advantages of the drying/heating convective system over the conventional system are as follows:

a) Homogenous heating, with constant and uniform removal from water – free and combined, and from bonding compounds. The uniform exit of water steam leads to smaller

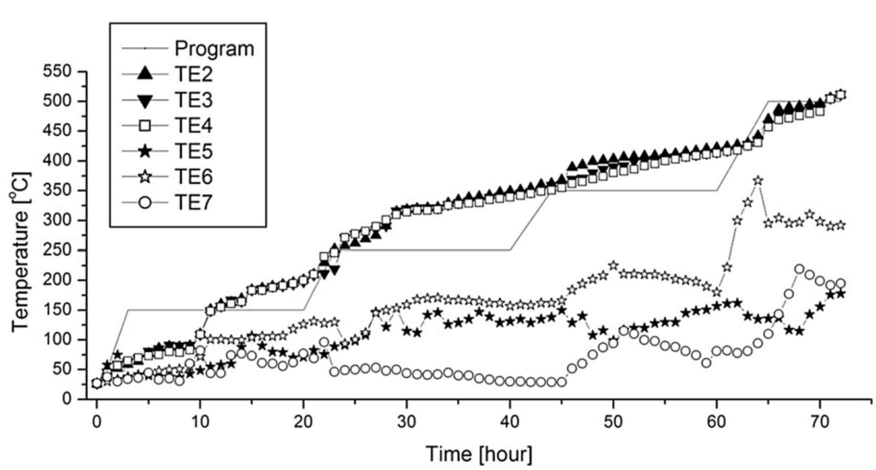

Fig. 7. Temperature behavior during conventional drying/heating curve of Runner #1 of BF #3.

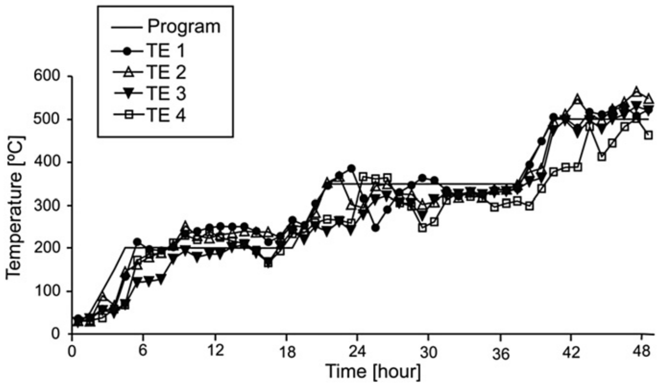

Fig. 8. Temperature behavior convective drying/heating curve of Runner #2 of BF #3.

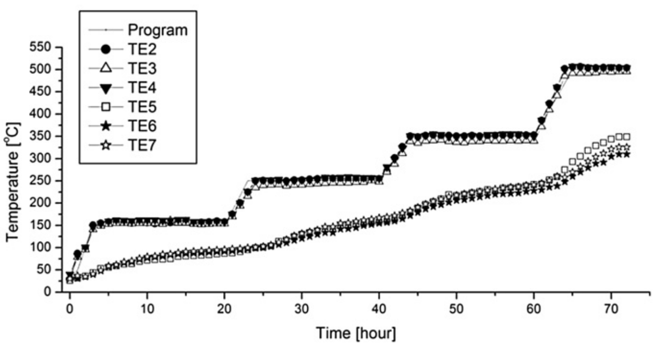

Fig. 9. Temperature behavior during convective drying/heating curve of Runner #3 of BF #3 covered with ceramic fiber lids.

capillaries, thereby minimizing later on the problems associated with metal and slag infiltration in the lining.

b) Uniform temperature distribution with steady heating rates. This lessens heat strains upon the lining, thus mitigating the likelihood of crack dissemination and explosion.

c) Uniform heat penetration, resulting in more favorable conditions to chemical reactions in the lining. This boosts material properties while lessening thermal shock risk during the first tapping in the Runner.

A comparison of the flame profile and characteristics are shows in Fig. 1 and Table 1.

Convective heating system comprises the following equipment:

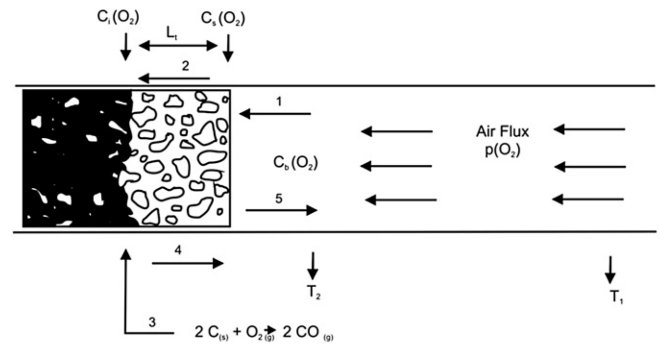

Fig. 11. Oxidation mechanism [2,3].

a) Complete combustion set with electric power interlock, UV-type flame sensor, temperature start and monitoring panels.

b) High-speed burner and fittings (hoses, safety valve systems, etc.).

c) "K"- type thermocouples and digital recorder to monitor drying/heating curve.

d) Temporary coverage for combustion set with ceramic fiber insulation.

The implementation of a convective heating system in the Blast Furnace Runners aimed to:

a) Measure Blast Furnace natural gas consumption – Runners, Tap hole Bonnet and PCI.

b) Cut down on Blast Furnace natural gas consumption:

b.1) Move from pro-rata consumption to measured consumption.

b.2) Rationalize heating curves.

c) Up Runner availability.

c.1) Streamline working conditions during lining demolition – men and machines.

c.2) Improve refractory lining performance.

d) Enable repair time for Tap hole Bonnets in BF outage schedule for Preventive Maintenance (max. 30 h).

e) Develop in the future on-line monitoring procedures for Runner wear profile in the critical regions – temperature versus remaining thickness.

2. Materials and methods

Table 2 shows, for reference purposes, the natural gas consumption of CSN Blast Furnaces #2 and 3, pro-rata consumption.

Fig. 10. Aspect of molded refractory blocks after industrial convective drying/heating curve.

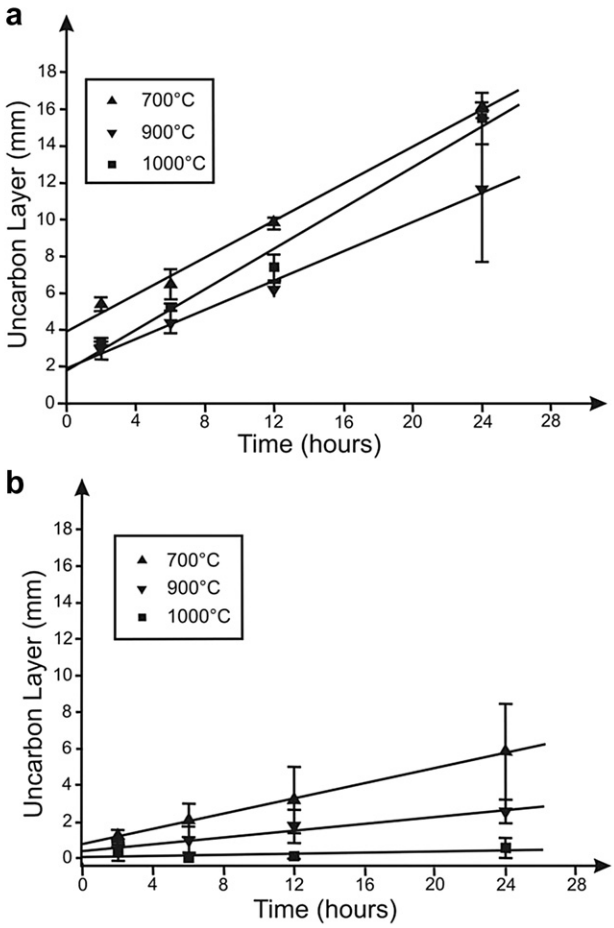

Fig. 12. Decarburization depth of refractory cement test specimens (a) without ceramic coating and (b) with ceramic coating [2,3].

In line with our strong commitment toward "Zero Accident", technical procedures and risk analysis of all activities related to the implementation of this new technology were produced, including Work Permit, sealing off Runner area, compulsory use of Protective Equipment, CO detector, leak test in connections and padlocking as well as safety warning signs on auxiliary equipment belonging to Cast House – mud gun and drilling machine.

In order to ensure an environmentally-friendly procedure, the installed system was particularly designed to use natural gas, consisting of high pressure hoses, manifolds, rotameters, pressure controlling valve, flow controlling valve, burners with flame protective nozzles and digital and cartographic temperature recorders.

To assess the technical and economic viability, the company Thermojet was hired, for a 3-month period, to provide drying and heating services in the Runners and Tap hole Bonnets of Blast Furnaces #2 and #3. Fig. 2 shows the installed thermocouple location to monitor the drying/heating curve of BF #3 Runners.

The burner position was defined studying the dynamics of the gas flow into the Runner. The chosen position is represented in Fig. 3. The burner positioned into the Bottom of Runner is illustrate in Fig. 4, in the detail are showed the heat flow parallel to the channel floor's. The photography documentation of the heat-up process facilities used on industrial trial of CSN BF #2 Runners are shown in Fig. 5.

3. Results and discussion

Throughout the whole industrial testing period, no accidents – be they of personnel, equipment, or environmental nature – were reported.

Tables 3 and 4 show the natural gas consumption measured during the drying/heating period of Blast Furnace #2 and 3 Runners and Tap hole Bonnets respectively, as well as a monthly and annual consumption projection, based upon refractory maintenance schedule. The annual gas consumption of BF #2 and B #3 is 7420 m^3. The natural gas consumption measured was substantially lower than that suggested on a pro-rata basis.

Fig. 6 shows a typical, conventional drying/heating curve of BF #3 Runners over a 6-day period of time, with a 2647 m^3 consumption of natural gas. Following the convective heating system implementation, the drying/heating curves of BF #3 Runners experienced an immediate shortening from 96 h to 72 h and, later on, down to 48 h, thereby reducing natural gas consumption and upping its availability.

Fig. 7 shows temperature monitoring during conventional drying/heating of Runner #1 of BF #3, totaling 72 h. Fig. 8 shows the drying/heating curve of Runner #2 of BF #3, totaling 48 h. As one can see, the actual curve is far away from that which was programmed, reveals low controllability of the conventional system.

Also, a major deviation was found between actual versus estimated temperature, which precluded an in-depth investigation into the whole potential of the new technology. This deviation was mainly brought about by the poor insulation of Runner covers. To circumvent this problem, ceramic fiber was installed to cover the Runner. Fig. 9 shows the convective drying/heating curve of Runner #3 of BF #3, covered with ceramic fiber, totaling 72 h.

Fig. 13. Aspect of molded refractory blocks, with ceramic coating on, following industrial convective drying/heating curve.

Fig. 14. Use of ceramic coating in CSN BF #3 Runners.

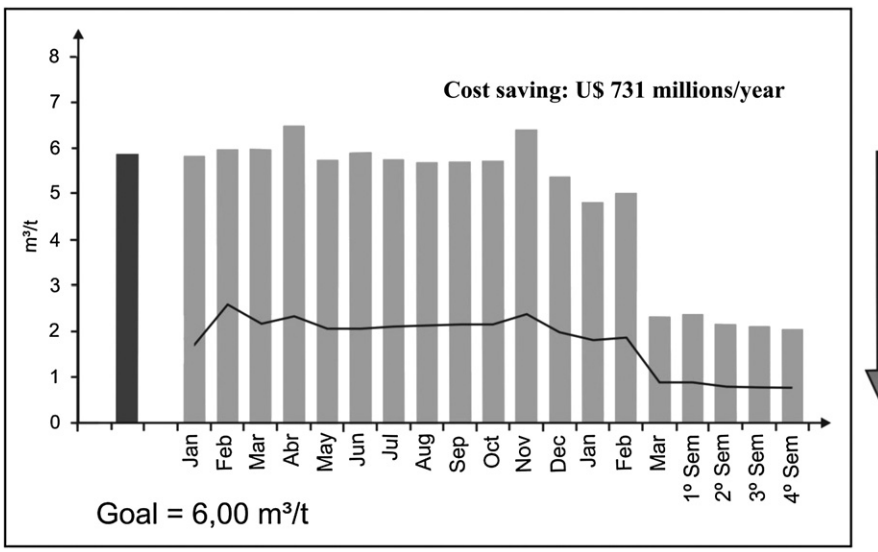

Fig. 15. Natural gas consumption reduction at BF #2.

Following Runner insulation improvement, it became clear the edge of this new technology in terms of controllability, with a negligible deviation between the actual and estimated curves.

The drawback to implement this new heating system turned out to be the oxidation of Runner refractory lining, as a result of the high amount of oxygen arising from combustion excessive air (3300%). Fig. 10 shows the aspect of the molded refractory blocks which were laid inside the Runner, and exposed to drying/heating industrial curve that evidence the oxidation in face of refractory block. Fig. 11 shows the oxidation mechanism of carbon by oxygen

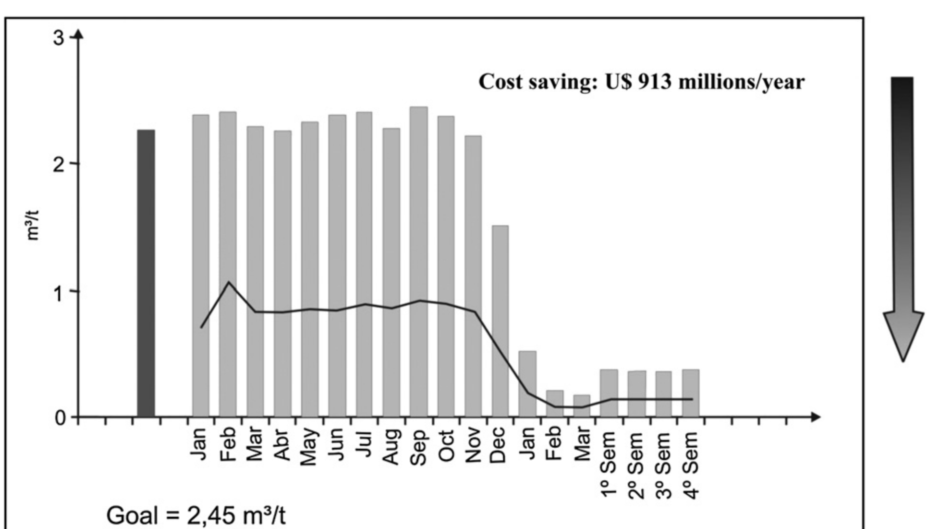

Fig. 16. Natural gas consumption reduction at BF #3.

of air flow. Refractory castable carbon is oxidized down to approximately 20 mm deep, thus creating new pores for hot metal and slag infiltration upon flowing into the operating Runner.

To tackle this problem, an agalmatolite-based ceramic coating was developed [13,14]. A Patent has been applied for in behalf of CSN/UFSCar, Brazilian University, and its technology was transferred to Saint Gobain [15], the company which provides refractory maintenance services at CSN BF Runners.

Fig. 12 shows the decarburization layer of refractory castable test specimens, with and without ceramic coating, subjected to temperatures ranging from 700 to 1000 °C for 24 h.

At low temperature ceramic coating is glazed, which turns its hot side impermeable to oxygen diffusion, while protecting it from Runner atmosphere effect. Fig. 13 shows the aspect of molded refractory blocks, with coating on, laid inside Runner, which were exposed to drying/heating industrial curve. By using this ceramic coating, decarburization depth is minimum.

Fig. 14 shows ceramic coating being applied in CSN BF #3 Runners.

The industrial trials conducted pointed to the technical and economic viability. Underpinned by these results CSN decided to implement the convective drying/heating technology in the Runners and Tap hole Bonnets of BF #2 and 3, from March and January/2004, respectively. This very same technology was introduced in other equipment too, such as: Torpedo Cars, Sintering Ignition Ovens, LD Converters, Slab Reheating Furnace, Lime Kilns, Steel Ladles etc.

Figs. 15 and 16 show gas natural consumption and cost reduction at BF #2 and 3, respectively, following implementation of this new technology.

4. Conclusions

The convective drying/heating technology proved to be viable from a technical and economic standpoint. The main results attained following its implementation were:

a) Repair of Tap hole Bonnets during BFs preventive maintenance;
b) Increase in BF #3 Runner availability (4 days/month); and
c) Cut down on natural gas cost, approx. U$ 1644 m/y. It goes without saying that this cost reduction was basically due to the change in the billing manner, which shifted from pro-rata to measured consumption.

This new technology, based on controlled cooling and heating, was also introduced in other equipment in the Steel Mill, with a number of benefits, such as:

b) Reduction in LD Converter repair time from 72 down to 54 h (22.000 metric tons of molten steel/year);
c) Reduction in Sinter #2 cooling time from 12 down to 5 h (5.700 metric tons of sinter/year); and
c) Reduction in Lime Kiln heating time from 74 down to 56 h (300 metric tons of lime/year).

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