POST COMBUSTION TIP FACE - THE SOLUTION TO INCREASE SCRAP AND REDUCE CARBON EMISSIONS*

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Abstract

The integrated plants suffer the need to adapt their processes to contribute to carbon reductions. One option of many BOF converters is the replacement of hot metal with scrap. Building on theories from the 80s and using modern computational mathematical simulation resources, Lumar developed an innovative lance tip with afterburner on the face. Patented product with the differential of being a lance with three tubes and supersonic post combustion nozzles. The results show an average increase scrap percentage, shorter blowing time and integrity of the lance conditions.

Keywords: BOF, post combustion, tip face, carbon emissions, scrap.

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1 INTRODUCTION

The global commitment to reduce carbon emission sources has gained vigor and rigour in recent years in the face of the speed of climate change. This need has been driven by free enterprise, but in many countries and even continents there are movements for a regulation of these emissions. In this sense, it is also already observed action of steel groups with the intention of adapting to the new reality, among these actions: shutdown of outdated plants, updating of control equipment, migration in certain groups of integrated plants to mini-mills by EAF.

For other integrated steel mills, a major effort to replace carbon emission sources. The Brazilian steel industry is notorious for the dominance of the use of charcoal in small blast furnaces and more recently in medium-sized blast furnaces. In steelworks, there is a tendency to replace the use of hot metal by scrap and other sources of metal oxides such as ore, pellet, sinter and briquette, the latter having great potential to reduce the environmental impact on the disposal of superfines in waste yards.

For this substitution it is necessary to perform a compensation in the thermal balance of the converters. An immediate solution is the oxidation of the bath with loss of metallic yield through the increase of iron oxide in the slag. However, there are alternatives.

The main one is the use of lance tips with face post-combustion. Post-combustion is the phenomenon of secondary reaction during blowing, to which oxygen reacts with carbon monoxide, the result of the primary reaction of oxygen with pig iron carbon, as shown in Figure 1.

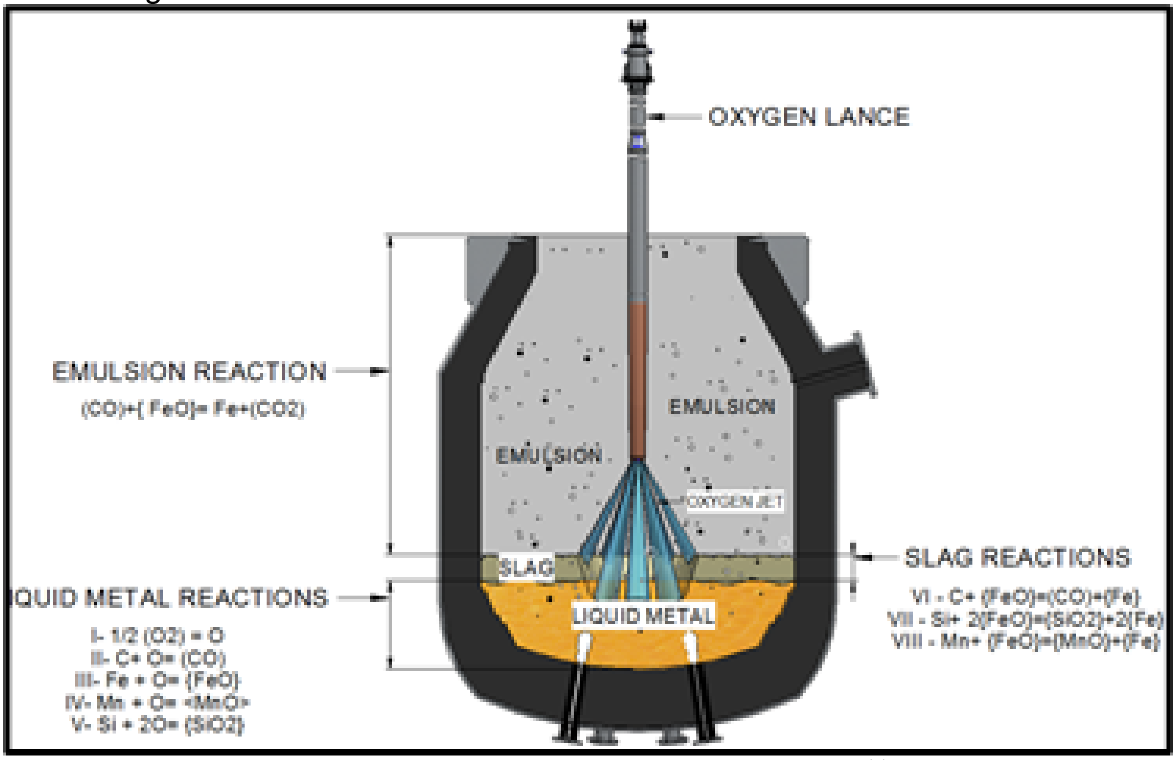

Figure 1 – Refining reactions in the BOFconverter(1).

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The post-combustion theme is not new, being much explored in the 80s and 90s(2-7). The oxygen values of the past studies point to values around 10%, causing a reduction in gas recovery, important resources that have gasometers and power generators and for heat a significant increase in the temperature of liquid steel, with negative impact on the converter refractories, overheating of the dedusting ducts as well as increased bath oxidation and increase in the average content of iron oxide in the slag. Regarding the lance(8-10), it is common to observe in plants with post-combustion resource of the 80s and 90s, the need for a line and instrumentation exclusive for secondary oxygen, being an investment as shown in Figure 3.

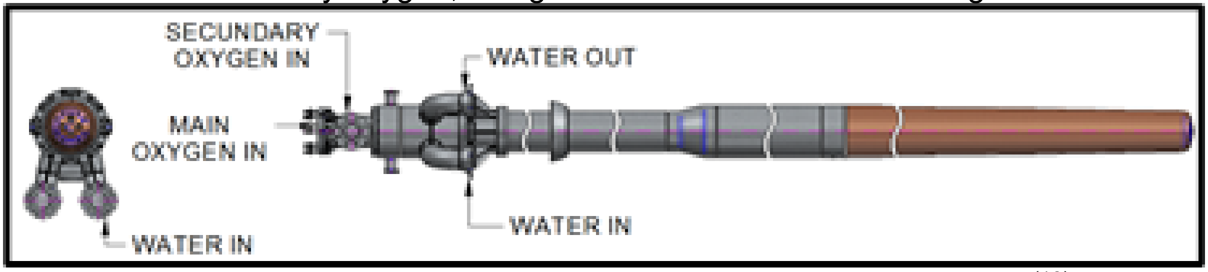


Figure 2 – Four pipes post combustion lance for BOF converter(10).

This article presents and discusses the use of post-combustion as a solution to reduce carbon emissions in the primary refining of steels via BOF converters and how the correct sizing allows the optimization of blowing operations, without the need to invest a line dedicated to secondary oxygen using Lumar Metals technologies.

2 METHODOLOGY

The work consisted of the combination of analytical calculations, computer simulations and industrial tests(15-17) after developments in cold models.

The analytical calculations were performed based on the equation developed by Lima(1) according to equation 1 presented below:

$$\frac{\pi}{2 \cdot K^2} \cdot P^* \cdot (1 + P^*)^2 \cdot \left[1 + (P^*)^{-2} \cdot \frac{1}{Eo^*}\right] = Fr^* \quad [1]$$

$$Eo^* = \frac{(\rho_{STEEL} + \rho_{SLAG}) \cdot g \cdot DBL^2}{\cos\theta \cdot (\sigma_{STEEL} + \sigma_{SLAG})} \quad [2]$$

$$Fr^* = \frac{\pi}{4} \cdot \frac{\rho_{GAS} \cdot (V_{EXIT} \cdot D_{EXIT} \cdot \cos\theta)^2 \cdot n}{(\rho_{STEEL} + \rho_{SLAG}) \cdot g \cdot DBL^3} \quad [3]$$

$$P^* = \frac{P}{DBL} \quad [4]$$

Where: ρ_{gas} - density of the gas at the nozzle outlet ($kg.m^{-3}$), g the acceleration of gravity (m/s^2), ρ_{steel} - density of liquid steel ($kg.m^{-3}$), P - penetration jet (m), σ_{steel} - surface tension of liquid steel ($N.m^{-1}$), DBL - distance bath lance (m), V_{exit} - speed at nozzle outlet (m/s), D_{exit} - representing nozzle output diameter (m), K - compensation factor, θ - angle of inclination of the nozzle, σ_{slag} - surface tension of the slag ($N.m^{-1}$), σ_{steel} - surface tension of steel ($N.m^{-1}$), ρ_{mix} - density of the mixture of steel, slag and gas ($kg.m^{-3}$), n - number of nozzles, P* - dimensionaless penetration of the jet, Eo* - modified number Eötvös and Fr* - modified Froude number.

Equation 1 was used to determine the penetration of primary and secondary oxygen on the bath surface. Considering a trigonometric study(13), the influence of bubbling and the slag layer(14), the projection of the jets on the metallic bath was determined, as shown in Figure 3.

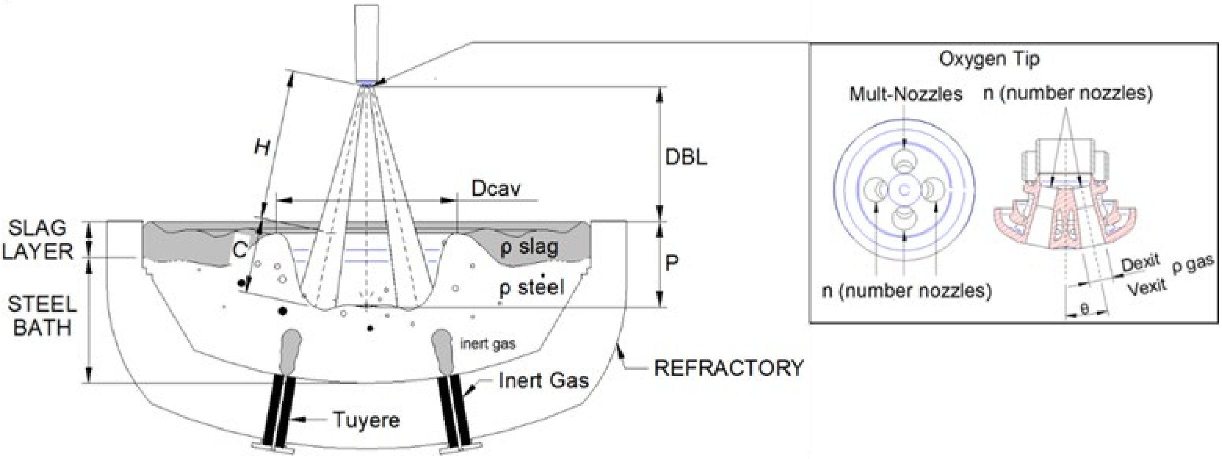


Figure 3 – Projection of the oxygen jet on the metal bath surface.

The premises for development were:

- Increase of 22% over the current weight of scrap charged;
- Maintain the same jet penetration as the current main nozzles;
- Obtaining post-combustion on the face from the main oxygen in order to maintain average flow;
- Increase the projected area of the secondary jets over the bath;

The numerical simulation for the model considering two phases in the metal bath: metal and slag and interaction with the oxygen jet was modeled by the volume of fluid. Not considered the effect of the tuyeres.

The simulations were solved by the finite volume method for a temporal and spatial discretization.
Then the system of equations mass, momentum, energy are solved together with equation for convective transport for a fraction of volume α according to the set of equations presented.

$$\frac{\partial \rho}{\partial t} + \nabla(\rho U) = 0 \quad [5]$$

$$\frac{\partial}{\partial t}(\rho U) + \nabla(\rho U U) = -\nabla \mathrm{p} + \nabla\{(\mu + \mu_t)(\nabla \mathrm{U} + (\nabla \mathrm{U})^t)\} + \rho g + F_s \quad [6]$$

$$\frac{\partial \alpha}{\partial t} + \nabla(\alpha U) + \nabla(\alpha(1-\alpha)U_r) = \frac{\alpha}{\rho_g}\left(\frac{\partial \rho_g}{\partial t} + U\nabla\rho_g\right) \quad [7]$$

$$\mu = \alpha\mu_l + (1-\alpha)\mu_g \quad [8]$$

$$\rho = \alpha\rho_l + (1-\alpha)\rho_g \quad [9]$$

$$\rho_g = \frac{Mp}{RT} \quad [10]$$

Where t – time, U – fluid velocity, g – gravity vector, m_t – turbulent eddy viscosity, F_s – surface tension force in volumetric form, U_r – relative velocity between gas and liquid, α - volume fraction defined as a=0 for gas phase and α=1 for melt phase, μ - dynamic viscosity, ρ – density, subscripts g – gas and l – liquid, M – molar mass, R – ideal gas constant and T – temperature.

3 RESULTS AND DISCUSSIONS

Due to the growing need to reduce the HMR (Hot Metal Rate) in order to reduce carbon emissions by increasing scrap consumption, Lumar Metals has developed a range of nozzles with post-combustion on the face for this and other demands as shown in Figure 4.

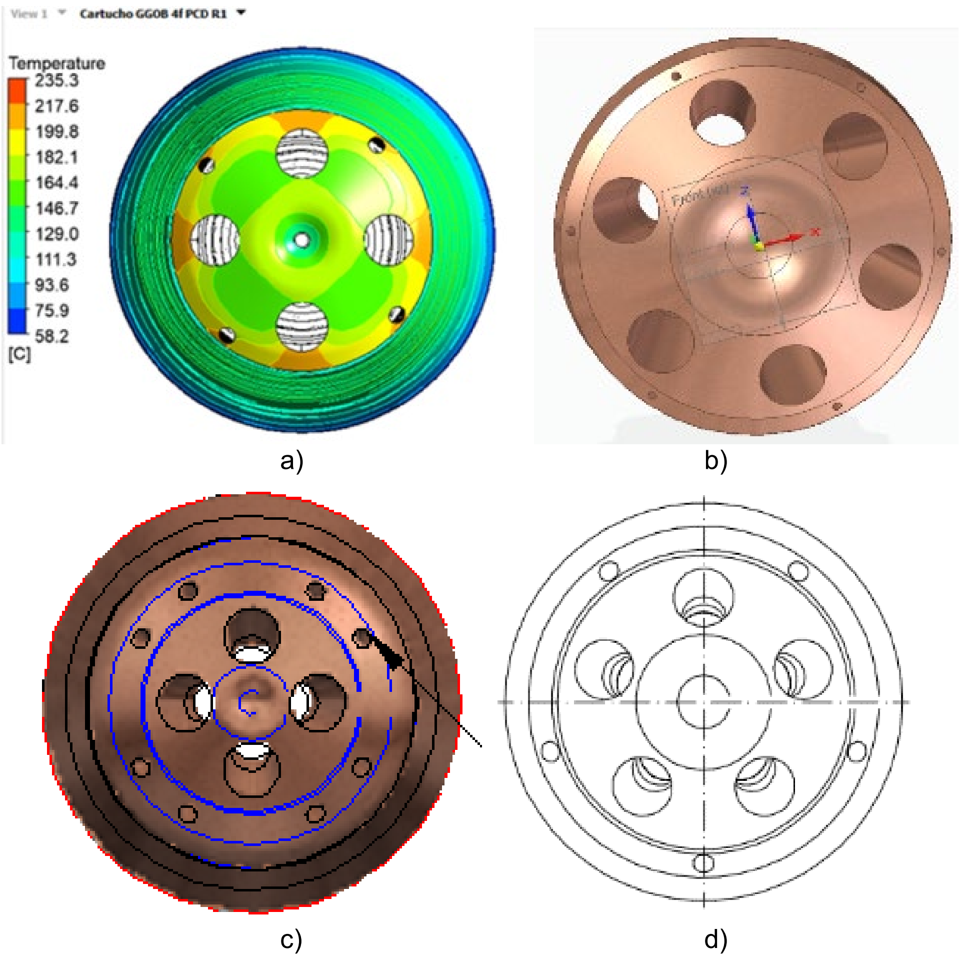


Figure 4 – Post-combustion face nozzles developed and manufactured by Lumar Metals.

Figure 4 shows a varied combination of major and secondary oxygen nozzles. This depends on the specific needs of each project, some of which are listed in table I.

From the parameters of table I, analytical calculations and computer simulations are performed in order to recommend the performances in process still in the development stage to be validated by the end users.

Table I – Parameters for post-combustion nozzle design.

Parameters
Production • **Reduction of HMR** • **Guarantee of ignition** • **Accelerate formation of slag** • **Increase of the rate of dephosphoration** • **Reduction of lance skulls** • **Increase in the consumption of briquettes such as:** ○ **metallic refrigerants** ○ **self-reducing** ○ **alloys and deoxidizers**
Maintenance • **Ease exchange** • **Ease replacement** • **Compatibility with conventional lance**
Lance • **Water flow** • **Water pressure** • **Lance diameter** • **Oxygen pressure** • **Maximum oxygen flow** • **Number of oxygen tubes** • **Number of primary nozzles** • **Number of secondary nozzles** • **Angle of primary nozzles** • **Angle of secondary nozzles**

3.1 ANALYTICAL CALCULATIONS

From a characteristic blow profile of the steel plant and the future need for the increase of scrap and thus the need for post-combustion on the face were determined the parameters for the project.elaboration

Figure 05 shows a characteristic blow profile and the introduction of face tip post-combustion.

Figure 5 shows several parameters of a blow: main oxygen flow, tuyere flow, secondary oxygen flow when there is a higher post-combustion module to avoid skulls formation and forecast of slag formation, by the direct addition of materials by top bins (slag rate sum additions) and in addition by mass balance considering oxidation reactions that reduce the mass of the liquid bath and increase the slag rate (slag rate regression).

Note that in the equation already contemplated the two possible consumption of secondary oxygen, in the face as well as in the upper part considering the objectives of cleaning the upper cone and oxygen lance. From the blow profile it is possible to perform the calculation of lance penetration, as shown in Figure 6

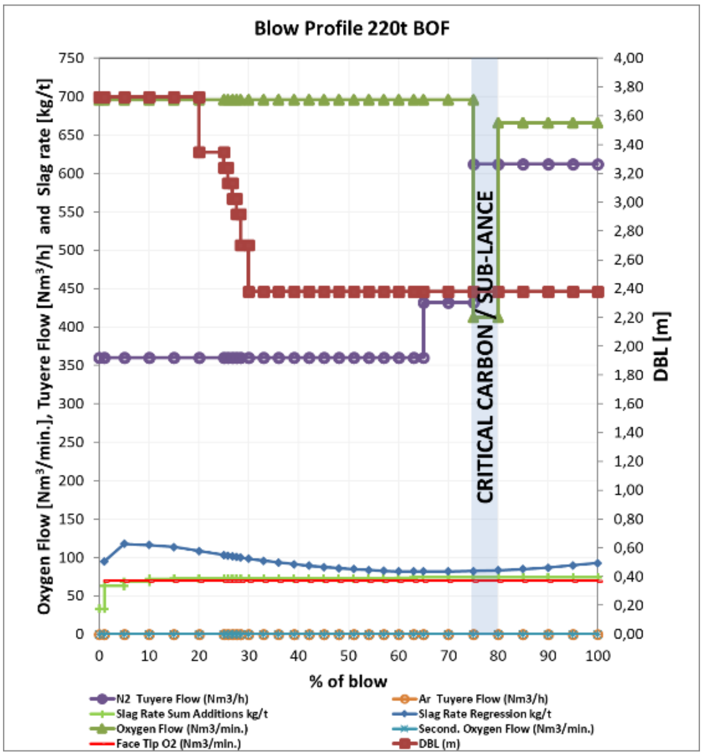
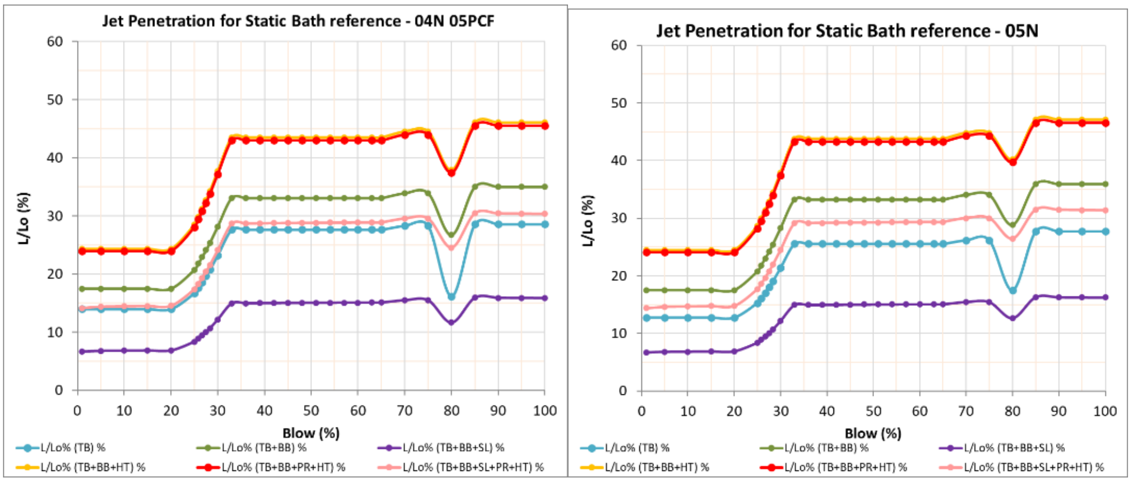


Figure 5 – Typical blow profile of 220t converter.



a) Post-combustion face lance tip b) Normal face lance tip

Figure 6 – Jet penetration calculations for nozzles with and without face post-combustion.

In Figure 6, according to the premise of maintaining oxygen jet penetration, small differences are observed even with the change from a traditional nozzle with 05 nozzles without post-combustion to one with 04 main nozzles and 05 secondary nozzles for post-combustion.It is also possible to observe the comparison of penetration with variations of the input parameters as described in Equation [8] and Table II.

$$\left| \frac{L}{L_o} := \frac{Oxygen\ Jet\ Penetration}{Static\ Bath\ Level} \right| \quad [11]$$

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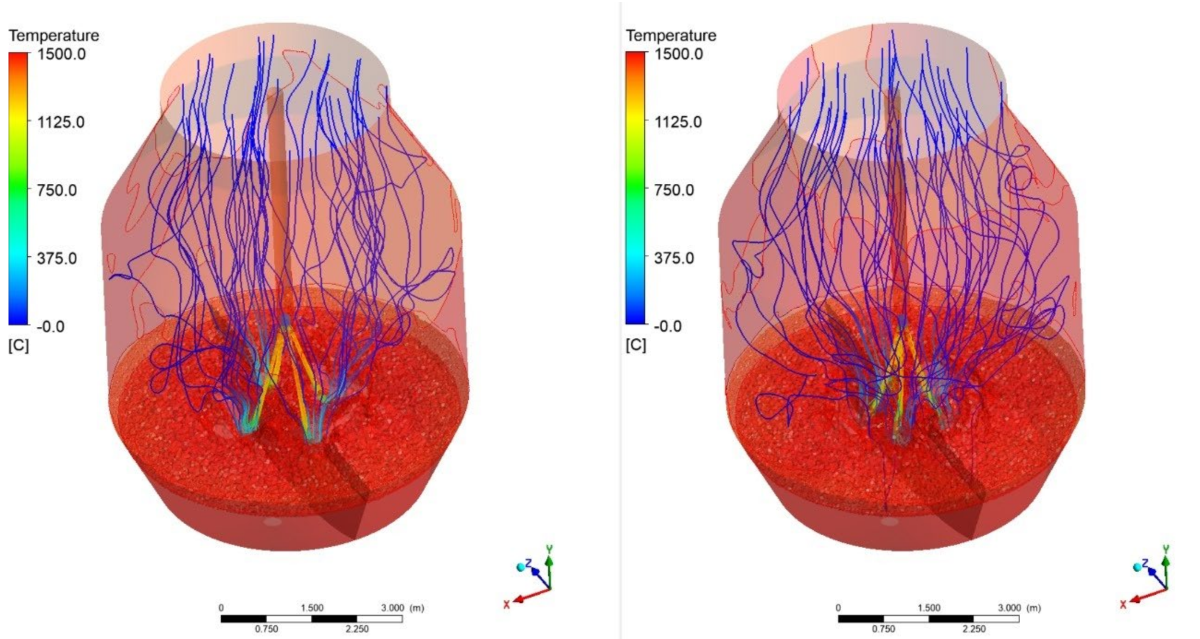
Table II – Parameters for post-combustion nozzle design.

L/Lo	Definition
L/Lo% (TB) TOP BLOW	Equation developed based on the momentum balance and K value obtained through empirical experiments in cold model followed by industrial applications for adjustment of lance height. In this condition, static bath level considered the final value of the metallic bath, that is, after melting and refining the loaded scrap and hot metal.
L/Lo% (TP+BB) TOP BLOW + BOTTOM BLOW	In this condition the influence of the bubbling flow is considered. During bubbling there is a change in the bath level (still considering the final volume or steel) due to the change in the density of the medium: liquid bath and gas. This new bath density is inserted into the momentum equation because it affects jet penetration. In certain cases, with a considerable increase in bubbling flow, the level displacement is proportionally greater than the increase in jet penetration.
L/Lo% (TB+BB+SL) TOP BLOW + BOTTOM BLOW + SLAG LAYER -	Considering the biphasic liquid bath consisting of a layer of slag and the mass of liquid metal is incorporated into the equation of moment the density of the slag as well as the surface tension. The layer of slag for the calculation of penetration is considered static at every moment of blow and 100% liquid. As additions of fluxes, energies, metal oxides and other elements that can make up the slag are made, the new volume of slag is recalculated through the density and diameter of the converter thus occurring changes in the height of the static liquid slag. In this case, the surface tension that absorbs part of the kinetic energy dispatched at the jet output and contributes to lower penetration values. The general behavior of the curve tends to have a lower penetration than the system with single-phase liquid.
L/Lo% (TB+BB+HT) TOP BLOW + BOTTOM BLOW + BOF HEAT -	Introduced the effect of the furnace environment temperature on the gas properties between the nozzles outlet of the to bath surface. In general, with the increase in temperature of the jet displacement environment, there is a drop in the density of this environment, with this lower resistance to the passage of the supersonic jet as well as less jet estrangement. Temperature rise provides behavior similar to jet coherence. Considering the momentum balance, an equation for adjusting K with the temperature increase was ARBITRATED.
L/Lo% (TB+BB+PR+HT) TOP BLOW + BOTTOM BLOW + BOF PRESSURE + BOF HEAT-	Possibility to modulate the pressure inside the BOF. Useful for reactors that have the device for suppressed combustion, which is possible to regulate the internal pressure of the converter by the admission or not of false air infiltrating through the gas capture system, as well as extend the study to other reactors such as DEGASSERS. In general, furnaces with high positive pressure promotes a resistance to the displacement of the jet, intensifies effects of the projection of gases. On the other hand, furnaces in depression, or close to vacuum despite promoting increased output velocity and consequently blowing flow, effectively are a resistance to the displacement of the jet that in turn transfers little kinetic energy to the bath, with low penetration.
L/Lo% (TB+BB+SL+PR+HT) TOP BLOW + BOTTOM BLOW + SLAG LAYER + BOF PRESSURE + BOF HEAT-	Final and complex version, all parameters worked with relative degree of independence are attached in a momentum equation. The slag layer acts as a great resistance to jet penetration, absorbing the energy of the jet like a "sponge". It is important to emphasize again, that the layer of slag is considered as a liquid layer supernatant to the layer of liquid bath bubbling up, composing a three-phase system. The density of the slag varies according to the variation of the chemical composition found in the mass balance, however the surface tension was considered constant. The penetration factor K in this condition is also a function of the temperature of the furnace environment and following the same equation ARBITRATED for temperature condition of the reactors, being the linear coefficient of these equations the respective K found in the cold models, here taken as in the reference temperature 298K.

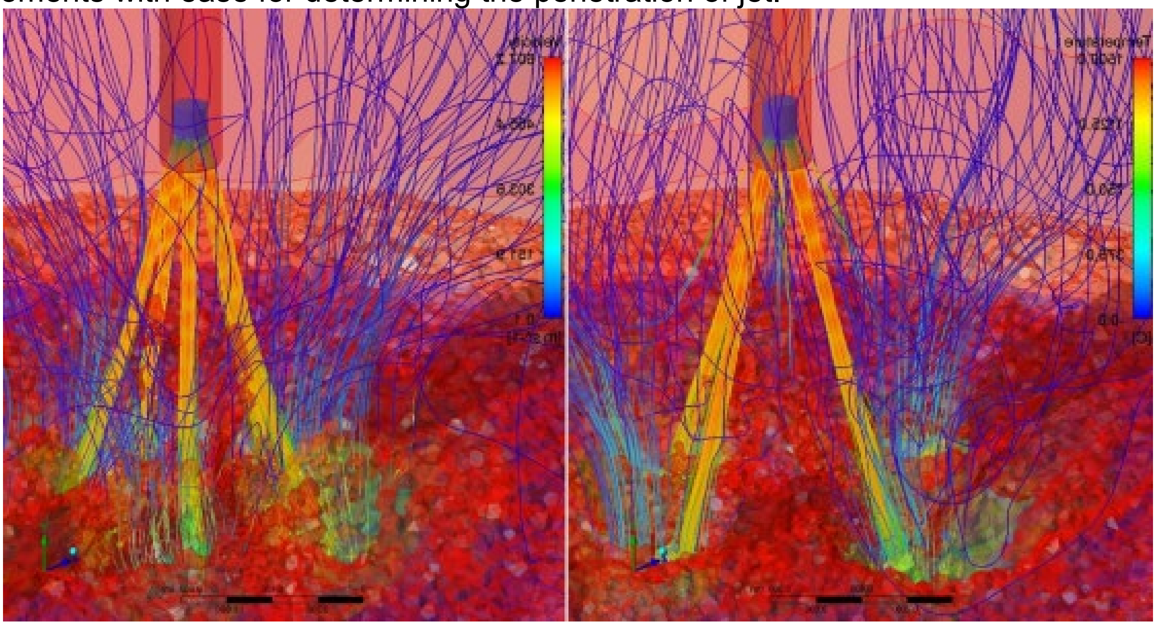
3.2 NUMERICAL SIMULATIONS



a) Post-combustion face lance tip b) Normal face lance tip

Figure 7 –3D view BOF converter with STATIC LAYER METAL AND SLAG.

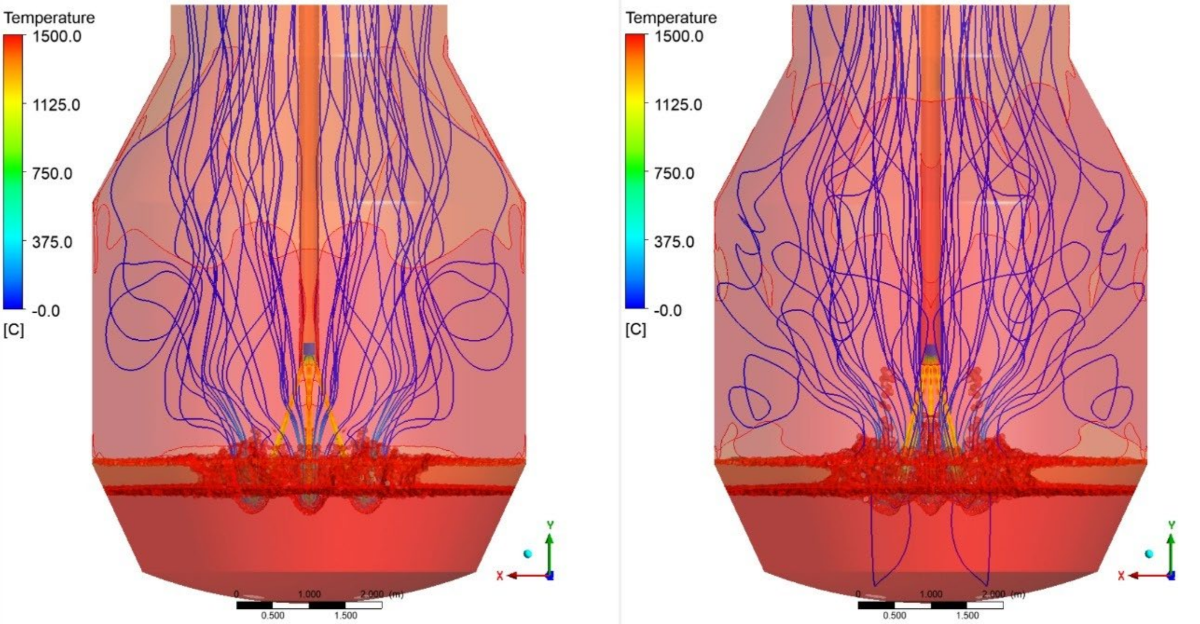
Figure 7 shows the result of the effect of the oxygen jet on the layer of slag and metal bath. It is a condition observed in industrial processes only when the blow is interrupted for a few minutes and the emulsion of the two predominant phases is segregated. However, this static layer, in particular, monophasic, is the condition of most mathematical models[14]. Only recently was proposed by Willian[1] an equation that considers other phases such as slag layer and bubbling, but still considered static. Thus, the result of the simulation is of special interest to confirm with results of analytical calculations the physical models on a reduced scale because they are moments with ease for determining the penetration of jet.



a) Post-combustion face lance tip b) Normal face lance tip

Figure 8 –3D ZOOM view BOF converter with STATIC LAYER METAL AND SLAG.

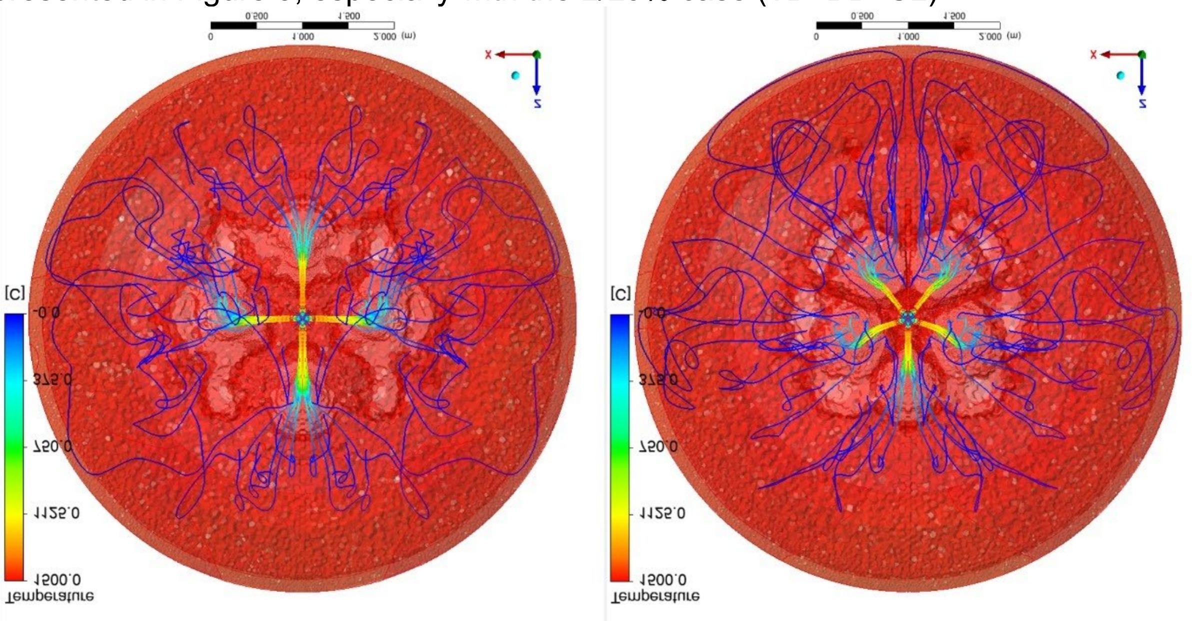
Figure 8 shows in greater detail the interaction of the jet with the bath, being in fact the first contact with the slag in the static layer. The high surface tension of the slag inhibits the penetration of the jet when compared to single-phase simulations of the liquid bath. With this, first begins an effort of the jet to break through the layer of slag and then obtain some penetration into the metal bath.



a) Post-combustion face lance tip b) Normal face lance tip

Figure 9 – Side 3D view BOF converter with STATIC LAYER METAL AND SLAG.

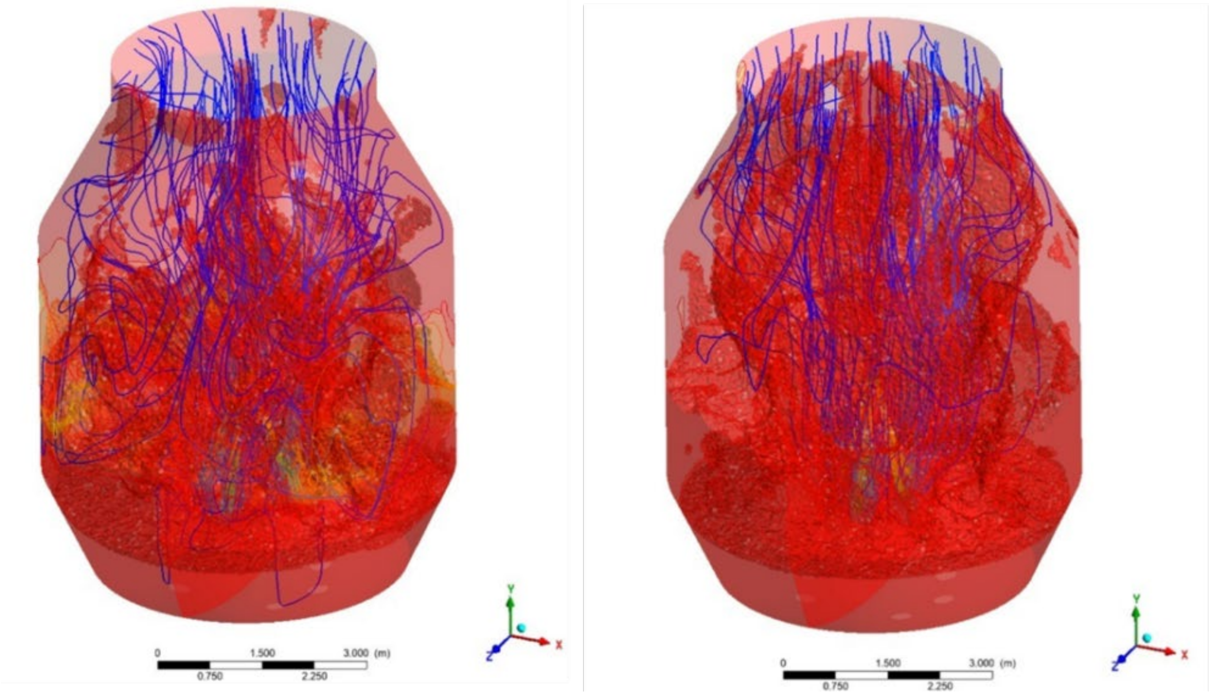
Figure 9 shows that the penetration obtained by the numerical simulation from static layers is very consistent with the values obtained through the analytical calculations presented in Figure 5, especially with the L/Lo% case (TB+BB+SL).



a) Post-combustion face lance tip b) Normal face lance tip

Figure 10 – Top 3D view BOF converter with STATIC LAYER METAL AND SLAG.

Figure 10 shows a top view. It is possible to notice the conceptual difference between the current nozzle and the nozzle with afterburner. This change was necessary to ensure a good cooling design of the face of the afterburner nozzle. However, the change from 05 to 04 outlet nozzles was compensated with the increase of the angle with the vertical and higher oxygen pressure. These changes aim to maintain the penetration of the main nozzles and expand the projected area of the jet over the bath. The secondary nozzles act between the main nozzles ensuring a jet cover at close range but covering a larger area, because the angle with vertical is close to double when compared to the main nozzles.

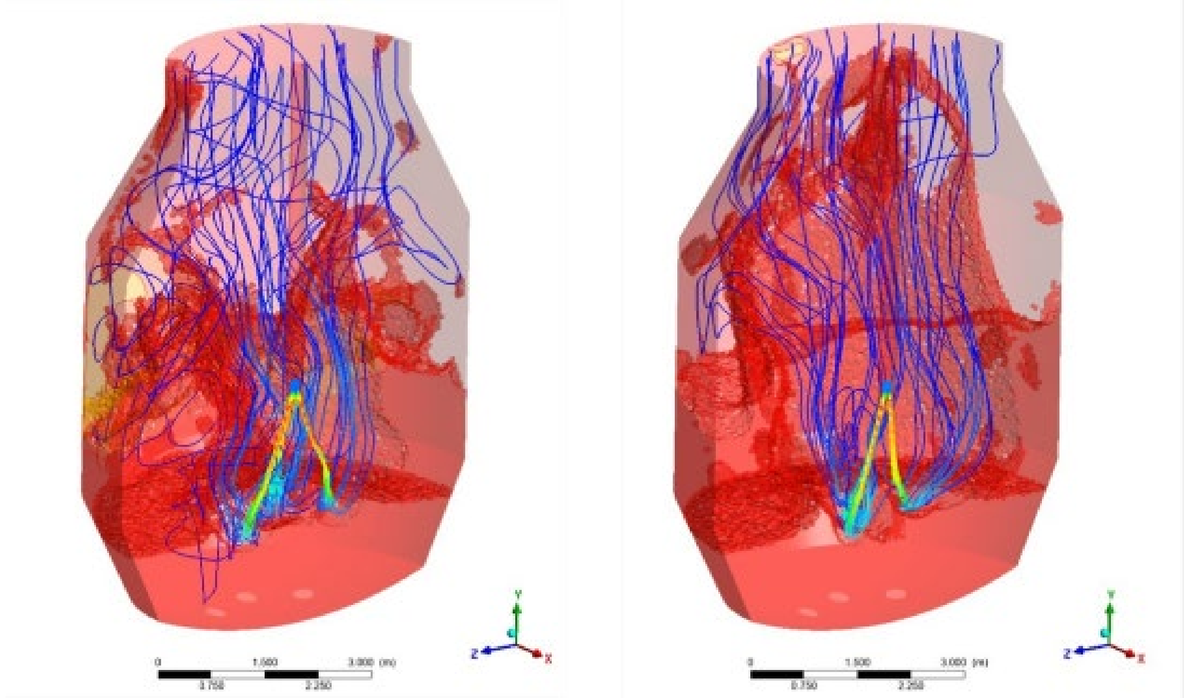


a) Post-combustion face lance tip b) Normal face lance tip

Figure 11 – 3D view BOF converter with FOAM.

Figure 11 shows the behavior of the emulsion. The simulations do not yet consider the chemical reactions and heat transfers that occur along the blow. However, to allow the simulation of the emulsion, the average properties of its constituents were considered: metal, gas and slag. Thus a three-phase system came to be represented by a single-phase system.

It is possible to notice in both images the jet force on the emulsion and how this is launched to the high converter regions, reaching regions of the upper cone. For the current nozzles, it is noted that the emulsion is concentrated around the oxygen lance and with the post-combustion lance due to the angle and greater penetration the emulsion has a shorter height range and concentrates in the cylindrical region of the converter, moving away from the lance.



a) Post-combustion face lance tip b) Normal face lance tip
Figure 12 – 3D view BOF converter with FOAM.

Figure 12 shows a cut of the simulation of the single-phase condition of the emulsion. The opening of the angles of the main and secondary nozzles increases the projected area and changes the emulsion vectors concentrating on lower layers of the converter, cylinder region. This concentration of mass intensifies the reactions and contributes to greater effectiveness of the post-combustion in the transfer of heat and rates of decarburation by the main nozzles, since the penetration compensated by the increase in oxygen pressure. Added to this is the beneficial effect of removing materials from the boom and upper cone of the converter, avoiding the formation of skulls.

4 CONCLUSION

The methodology for determining the post-combustion nozzle allows to conclude:

- Equation 1 includes a greater number of industrial parameters and allows the evaluation of jet penetration with different reactor conditions;
- The penetration result presented by the numerical simulation has a good similarity with the values found by the analytical calculations;
- The geometry of nozzles with face post-combustion are influenced by external conditions, the increase in energy and area projections, as well as internal conditions, in particular, guarantees of good cooling.

The design of the nozzle with face post-combustion presents the differentials:

- Penetration slightly higher than the nozzle 05 nozzles, due to the influence of the jet pressure to compensate for the increase in the angle with the vertical;
- Reduction of blowing time due to the increase in scrap;
- Greater coverage area with the angles of the secondary nozzles;
- Concentration of emulsification and intensification of the reaction rate in low regions of the converter;
- Increased ignition effectiveness.

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