MODELLING OF THE “K” COMPENSATION FACTOR OF THE MOMENTUM BALANCE EQUATION IN A METALLIC BATH IN THE LD *

Willian dos Reis Lima[1]
Maurício Covcevich Bagatini[2]
Bernardo Martins Braga[1]
Breno Totti Maia[1]
Roberto Parreiras Tavares[2]
Ana Tereza dos Santos Dias Moreira[2]
Ana Luiza Vasconcelos e Silva[2]
Pedro Henrique Araújo[2]
Gaelle Laure Siemou Tchoupo[2]

Abstract

This paper presents a theoretical, experimental, and practical study on the momentum balance equation, and the compensation factor “K” term, which is responsible to measure the lost energy of the oxygen jet going out nozzle until metallic bath. The complete domain about this factor and their correct application promote reductions process times and productivity gains, but it has not been a target of study by researchers in this area. Based on the study theoretical and experimental about momentum balance equation evolution the new equation proposed fixed a convergence problem existing in the last equation found in the literature. Three industrial application proposal of the equation was applied to the 340t converter. Effectiveness comparative of the blow profile between the new equations x Masazumi was made and the new equation got 23% of the effectiveness in jet penetration evaluation. The proposal to Slagsplashing profile can be calculate due to the equation convergence. This practice allows the preliminary analysis can be done before the application in the process converter. Similarly, the Burn bottom profile was proposed. The preliminary analysis will allow the practice to be evaluated and made safely, reducing the risk of accidents. The trial results show the importance of the increase the process parameters in the cold model trial thus representing the industrial process correctly. The values of the compensation factor “K” were obtained for different nozzles and conditions and can be applied in mathematical models.

Keywords: LD converter; Jet penetration; Compensation factor "K"; Cold Model.

---

[1] *Lumar Metals, Rodovia MG 232, km 09, 70, Santana do Paraíso, Minas Gerais, Brazil, ZIP:35167-000. Phone: +55 (31) 3828-1000. Email: breno.totti@lumarmetals.com.br willian.lima@lumarmetals.com.br*

[2] *UFMG -Universidade Federal de Minas Gerais, Belo Horizonte, Brazil. Email: leandrorocha@demet.ufmg.br .*

1 INTRODUCTION

The oxygen jet penetration in the LD converter's metallic bath is considered the main parameter during blowing because it is responsible for determining the reactor's metallurgical reaction rates. Besides removing carbon from the hot metal, other impurities, such as phosphorus, silicon, manganese, and sulfur, are removed due to oxygen interaction with the metallic bath. The agitation provided by the kinetic energy from the oxygen jet and the chemical reactions is the most crucial to obtain the slag's spontaneous emulsification and increase the heat transfer [1]. Therefore, it is necessary to understand the interaction characteristics between supersonic oxygen jets and the metallic bath to obtain the LD converter's stable operation and high operational efficiency. In the early 1960s, Banks and Chandrasekhara[1] studied the impingement of a gas jet onto a liquid surface and established the first fundamental relationship between the jet momentum and the penetration depth:

$$\frac{\dot{M}}{\rho_l g H^3} = \frac{\pi}{2K^2}\frac{P}{H}\left(1+\frac{P}{H}\right)^2 \qquad [1]$$

Where M is the gas momentum flow rate, ρ_l is the density of the liquid, *P* is the maximum depth of the cavity, and H is the lance distance to the liquid surface, K is the compensation factor K. Szekely and Themelis made the next actualization in jet penetration equation in 1971. Parameters as steel and gas density were increased.

$$\frac{1}{2}\ \rho_{gas}\ V_{jet}^2 = g\ \rho_{steel}\ P + \frac{2\ \sigma_{steel}}{r_{cav}} \qquad [2]$$

Where ρ_{gas} is the gas density at the nozzle exit (kg.m^{-3}), V_{jet} is the jet velocity (m/s), g is the acceleration due to gravity (m/s^2), ρ_{steel} is the liquid steel density (kg.m^{-3}), P is jet penetration (m), σ_{steel} is the liquid steel surface tension (Nm^{-1}), r_{cav} is the radius of the cavity formed by the jet penetration in the slag (m). Some new authors have carried out improvements for the jet penetration equation. Meidani et al. [4] inserted new parameters into the kinetic energy term:

$$\frac{\pi\ \rho_{gas}\ V_{exit}^2\ D_{exit}^2}{4\ \rho_{steel}\ g\ DBL^3} = \frac{\pi}{2K^2}\ \frac{P}{DBL}\left(1+\frac{P}{DBL}\right)^2 \qquad [3]$$

Where V_{exit} is the gas velocity at the nozzle exit (m/s), DBL is the bath lance distance (m), and "K" is the compensation factor. Then, Allam [5] inserted the term of the nozzle angle with the vertical in the jet penetration equation. This term was developed for the mathematical modeling of an electric furnace. However, it can be applied to the mathematical modeling of LD converters. The modified equation is:

$$\frac{M\ \cos^3\theta}{\rho_{steel}\ g\ DBL^3} = \frac{\pi}{2K_2^2}\ \frac{P}{DBL}\left(\frac{P}{DBL}+\ 1\right)^2 \qquad [4]$$

$$M = \frac{\pi}{4}\rho_{gas}\ V_{jet}^2\ D_{exit}^2 \qquad [5]$$

The M is the jet's initial momentum rate, and θ is the nozzle angle with the vertical. Maia et al[6] proposed recent updates in the jet penetration equation. Two basic terms have been inserted that take into account the effects of multi-nozzles and the slag layer. This equation was the last improvement found in the literature:

$$\frac{\pi}{2K^2}\frac{P}{(DBL+P)}\left(1+\frac{1}{P^2}\frac{\cos\theta(\sigma_{steel}+\sigma_{slag})}{\rho_{mix}\,g}\right)=\left(\frac{\pi}{4}\frac{(\rho_{gas}\,V_{exit}^2\,D_{exit}^2\cos^2\theta\,n)}{\rho_{mix}\,g\,(DBL+P)^3}\right) \qquad [6]$$

Where σ_{slag} is the surface tension of the slag ($N.m^{-1}$), σ_{steel} is the surface tension of the liquid steel ($N.m^{-1}$), ρ_{mix} is the mixture density composed of steel, slag, and gas ($kg.m^{-3}$). It is noteworthy that, in the equations presented, all parameters depend on variables related to the blowing process or nozzle configurations, except the compensation factor "K."

The compensation factor "K" was inserted in the jet penetration equation due to the necessity of positioning the oxygen lance from the metallic bath. Because of this positioning, the oxygen jet affected is by phenomena in the LD converter. These phenomena, such as internal converter environment, jet degradation, jet coalescence, and emulsion, act as resistance to the jet flow, reducing the jet penetration in the metallic bath. Therefore, the use of the compensation factor “K” in the jet penetration equation is necessary since it is the term that measures the resistances to the kinetic energy transfer between the nozzles exit and metallic bath. Although be an important term to jet penetration equation and operational result the compensation factor “K” is not studied as needed. Table I, are listed the compensation factor “K” values found but the literature doesn't show how were obtained except Maia et al.[6] who obtained by laboratory trial of cold modeling the “K” values, in which it is considered some blowing process parameters: height lance, oxygen flow, and nozzle number.

Table I - “K” values found in the literature

Reference	Autores	Year	K Values
[8]	Folsom *et al.*	1949	5,13
[19]	Albertson *et al.*	1950	6,4
[1]	Banks and Chandrasekhara	1963	7,9
[20]	Davenport *et al.*	1966	7,2
[21]	Wakelin	1966	6,9
[3]	Szekely and Themelis	1971	7,5
[4]	Meidani *et al.*	2005	11,05 e 12,04
[17]	Sung S. Park	2009	7,82
[10]	Neslihan Dogan	2009	7,9
[11]	Allam	2011	7,4
[18]	Mingming Li *et al.*	2015	5,13 e 11,5
[6]	Maia *et al.*	2016	5,22 4,58 4,26 3,32

Hence, if the compensation factor "K" is not common be used in the jet penetration equation, the kinetic energy losses that occurred in the oxygen jet path from the nozzle exit until the metallic bath would be neglected, and the results would be inaccurate. This study has been objecting to evaluate the effects of process variables and tip configurations in the jet penetration and to propose a new equation for calculating the jet penetration and the compensation factor "K." It was also determined the compensation factor "K" for configuration with, 3, 4, 5, and 6 nozzles.

2 METHODOLOGY

The study was separated into 2 phases: Experimental - Physical modeling in the laboratory and Development of the momentum balance equation by the experimental laboratory data.

2.1 Apparatus experimental

A top-blown gas jetting system was constructed by scaling down a commercial 340ton BOF by ten times. In the trial, compressible air was used to represent oxygen gas, while oil and water for the slag and metal, respectively. The dynamic similarity between the scaled-down model and the real system was maintained through the modified Froude number, Eotvos number, and Energy agitation (Table II), as commonly done in the trial l studies of BOFs. It is important to be pointed out here that a real BOF steelmaking system is generally non-isothermal, which therefore contributes to gas expansion. It is extremely difficult, if not impossible, to represent such conditions by a cold model as used in our study and many others, although this model has been widely used to study BOFs in the literature. How to overcome this problem one possible solution is to develop a computer model, which can reproduce the multiphase flow and thermochemical behaviors in a complicated BOF reactor.

Table II - Dimensionless number

	Definition	Industrial Model	Cold Model
Fr^* two phases	$Fr^* = \frac{Inertia\ force}{Gravitational\ force}$	0,129	0,129
Fr^* three phases		0,097	0,069
Eo*	$Eo^* = \frac{Gravitational\ force}{Surface\ tension\ force}$	1,58E+05	1,58E+04
E*		0,00013	0,00013

The trial setup mainly consists of a transparent vessel of the acrylic, a jetting lance with different configurations of the nozzles (3, 4, 5, and 6), and an air supply system, as shown in figure 1. Table III list the dimensions of the scaled-down acrylic converter and table IV the dimensions of the different nozzles used.

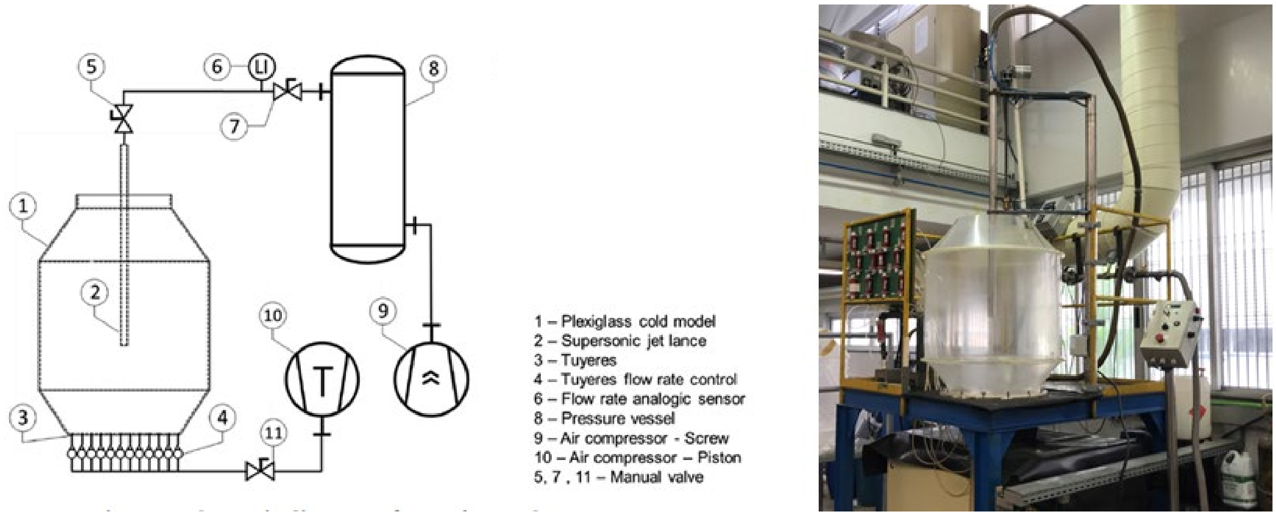


Figure 1 Schematic diagram of the trial arrangement

Table III - Dimensions acrylic converter

Unit	Data	Industrial Model	Cold Model
	Scale	1	1/10
m	Furnace Diameter	7,16	0,72
m	Furnace Height	10,09	1,00
m	Metallic bath height	1,75	0,175

Table IV - Dimensions Nozzles

Unit	Data	Industrial Model				Cold Model			
#	Nozzles options	3	4	5	6	3	4	5	6
m	Exit diameter	0,034	0,016	0,05	0,052	0,0049	0,0042	0,0038	0,0035
m	Throat diameter	0,039	0,02	0,042	0,042	0,0037	0,0032	0,0029	0,0026
#	Nozzles Angle	8°	10°	14°	17,5°	8°	10°	14°	17,5°

2.1 Experiments

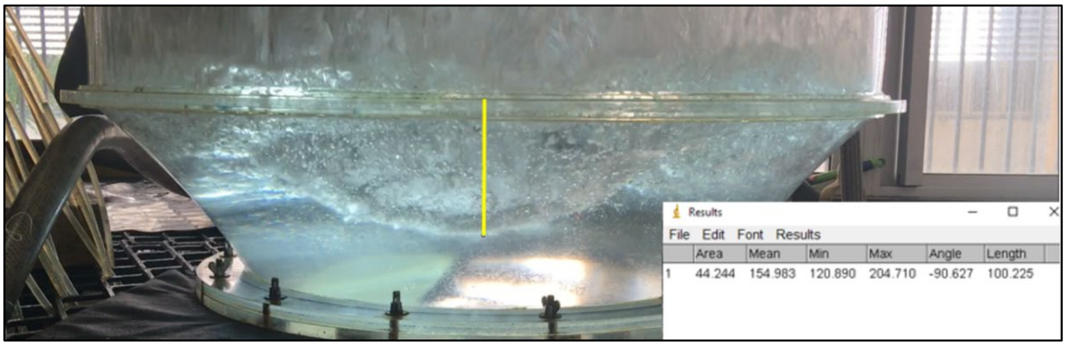
The trial matrix was designed by the complete factorial method, with repeated at least two runs to minimize the measurement errors [8]. The main process variables (nozzle number, DBL, Air flow, and Tuyere flow) were used in this trial. Table V shows the variables used and the trial I matrix defined. The matrix was applied in trial two-phase (air + water) and three-phase (air + water + oil) systems. One hundred twenty-eight trials were performed.

Table V - Trial matrix

Nozzles number (#)				DBL *(m)*	Air Flow *(Nm³/h)*	Tuyere Flow *(Nl/min)*
3	4	5	6	380	130	0
						32
					160	0
						32
				450	130	0
						32
					160	0
						32

In the measurement, the impingement of gas jets on a single-layer (two-phase) liquid (water) was first considered. Then, oil colored with oil-based blue aniline with the viscosity of 0,03 Pa.s, density of 925 kg/m^3, and surface tension of 0.029 N m/1 was added over the water to study the cratering process in the two-layer (three-phase) liquids system. The oil layer used was 15,5mm.

The videos and images of jet penetration were recorded and the image sequences were then selected to determine the jet penetration using a software ImageJ for each variable considered. Figure 2 illustrates a typically processed image, where the "Length" is corresponding to the jet penetration.



	Area	Mean	Min	Max	Angle	Length
1	44.244	154.983	120.890	204.710	-90.627	100.225

Figure 2 Processed image

2.2 Equation of the jet penetration (P) and the compensation factor "K"

The new development of the equation was based on Maia et al.[6] equation.

$$\frac{\pi}{2\cdot K^2}\cdot\frac{P}{DBL}\cdot\left(1+\frac{P}{DBL}\right)^2\cdot\left[1+\left(\frac{P}{DBL}\right)^{-2}\cdot\frac{\cos\theta\cdot(\sigma_{STEEL}+\sigma_{SLAG})}{(\rho_{STEEL}+\rho_{SLAG})\cdot g\cdot DBL^2}\right]=\frac{\pi}{4}\cdot\frac{\rho_{GAS}\cdot(V_{EXIT}\cdot D_{EXIT}\cdot\cos\theta)^2\cdot n}{(\rho_{STEEL}+\rho_{SLAG})\cdot g\cdot DBL^3} \quad [7]$$

Where P is the jet penetration (m), DBL is the distance bath lance (m),σslag is the surface tension of the slag (N.m^{-1}), σsteel is the surface tension of the liquid steel (N.m^{-1}), $\boldsymbol{\rho_{steel}}$ is density steel (kg.m^{-3}), $\boldsymbol{\rho_{slag}}$ is density slag (kg.m^{-3}), $\boldsymbol{\rho_{gas}}$ is density gas (kg.m^{-3}), θ is the nozzle angle with the vertical, Vexit is the gas velocity at the nozzle exit (m/s), Dexit is the exit nozzle dimension (m) and g is the acceleration due to gravity (m/s^2). Simplifying equation 7 by dimensionless numbers: Penetration ($\mathbf{P}^*$), Eötvos ($\mathbf{Eo}^*$) and Froude ($\mathbf{Fr}^*$).

$$\frac{\pi}{2\cdot K^2}\cdot P^*\cdot(1+P^*)^2\cdot\left[1+(P^*)^{-2}\cdot\frac{1}{Eo^*}\right]=Fr^* \quad [8]$$

Disregarding the superficial tension effects:

$$\frac{\pi}{2\cdot K^2}\cdot P^*\cdot(1+P^*)^2=Fr^* \quad [9]$$

Defining the auxiliary variable X:

$$X=1+P^* \quad [10]$$

Applying equation 10 on the equation 9 it is possible apply over traditional cubic model:

$$X^3 - X^2 - \left[\frac{2\cdot K^2}{\pi}\cdot Fr^*\right] = 0 \qquad [11]$$

$$\mathrm{Y}^3 - \frac{1}{3}\mathrm{Y} - \left[\frac{2}{27} + \frac{2\cdot \mathrm{K}^2}{\pi}\cdot \mathrm{Fr}^*\right] = 0 \qquad [12]$$

Equation 13 has the depressed cubic model and has the analytical solution known. Their discriminant, Δ, is:

$$\Delta = -\left\{4\cdot\left(-\frac{1}{3}\right)^3 + 27\cdot\left[\frac{2}{27} + \frac{2\cdot \mathrm{K}^2}{\pi}\cdot \mathrm{Fr}^*\right]^2\right\} \qquad [13]$$

Therefore, we always have that Δ<0, since all the parameters of the expression above are positive. As a result, the depressed cubic equation has only one real root. This property makes the proposed solution method robust, that is, there is no risk of computing a physically meaningless solution, which could occur if the equation had multiple real roots. The solution to this problem can be conveniently written in terms of hyperbolic functions:

$$\mathrm{Y} = \frac{2}{3}\cdot \cosh\left\{\frac{1}{3}\cdot \operatorname{acosh}\left[\frac{9}{2}\cdot\left|\frac{2}{27} + \frac{2\cdot \mathrm{K}^2}{\pi}\cdot \mathrm{Fr}^*\right|\cdot\sqrt{9}\right]\right\} \qquad [14]$$

Applying equation 15 on the equation 14 we obtain the final jet penetration equation 16:

$$\mathrm{P}^* = \mathrm{Y} - \frac{2}{3} \qquad [15]$$

$$P^* = \frac{2}{3}\cdot \cosh\left\{\frac{1}{3}\cdot \operatorname{acosh}\left[1 + 27\cdot\frac{\cdot \mathrm{K}^2}{\pi}\cdot \mathrm{Fr}^*\right]\right\} - \frac{2}{3} \qquad [16]$$

Lastly, we apply in equation 17 the superficial tension effects:

$$\mathrm{Y} = \frac{2}{3}\cdot \cosh\left\{\frac{1}{3}\cdot \operatorname{acosh}\left[1 + 27\cdot\frac{\cdot \mathrm{K}^2}{\pi}\cdot\frac{\mathrm{Fr}^*}{\mathrm{Z}}\right]\right\} \qquad [17]$$

Where Z is:

$$\mathrm{Z} = 1 + (\mathrm{P}^*)^{-2}\cdot\frac{1}{\mathrm{Eo}^*} \qquad [18]$$

3 RESULTS AND DISCUSSIONS

3.1 Effect of the variables on the jet penetration

Figures 3 to 6 illustrate the results of the trial using the selected variables, respectively, in the conditions with two/three phases and bottom blowing activated or deactivated.

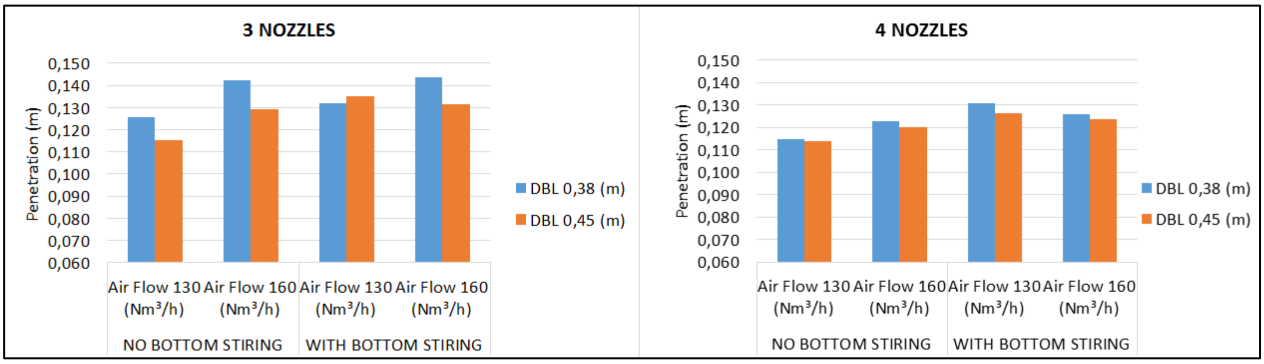


Figure 3 Trial 03 and 04 Nozzles - Two-phase model

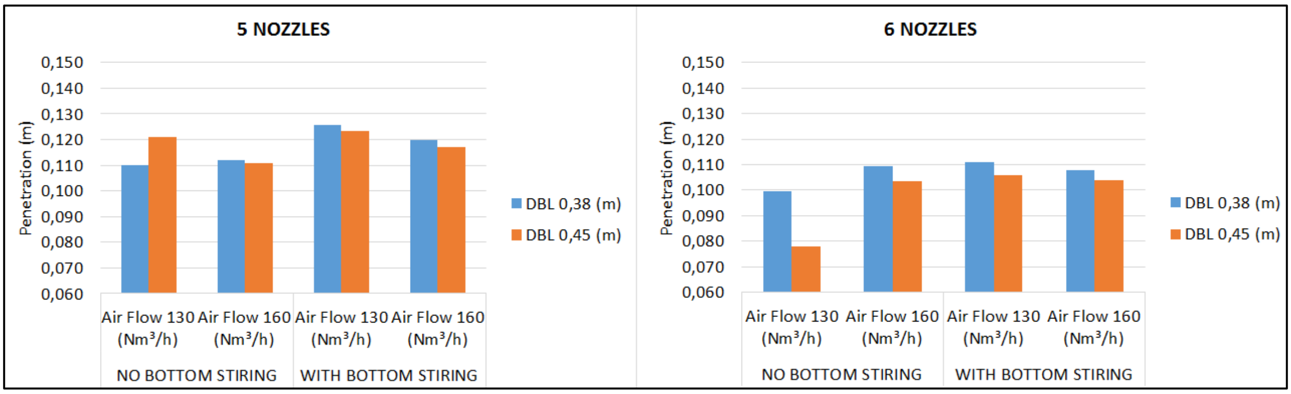


Figure 4 Trial 05 and 06 Nozzles - Two-phase model

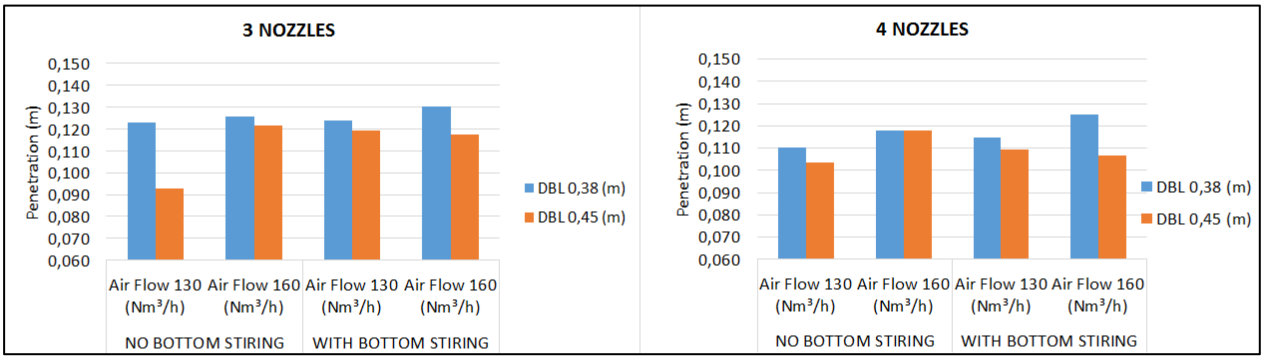


Figure 5 Trial 03 and 04 Nozzles - Three-phase model

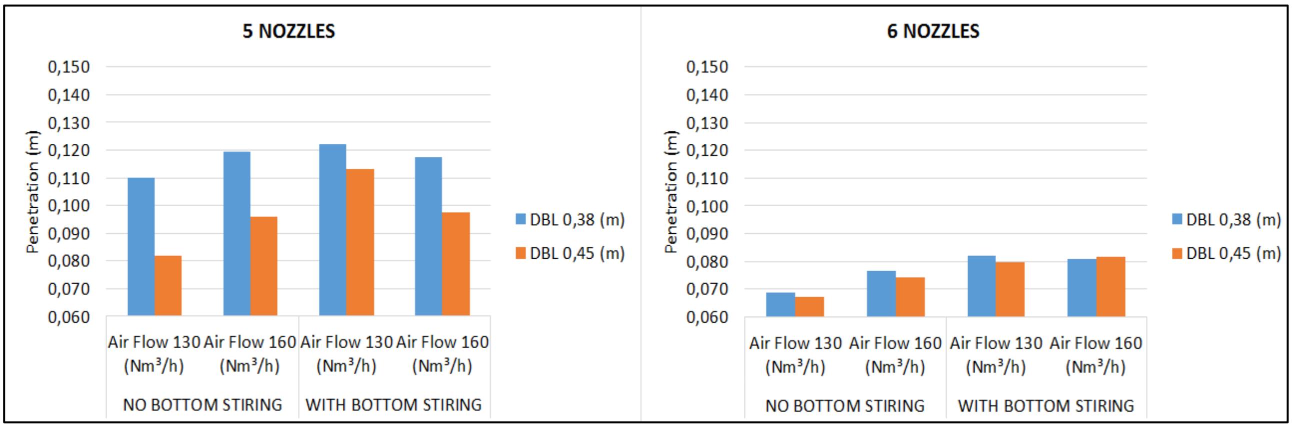


Figure 6 Trial 05 and 06 Nozzles - Three-phase model

The standard deviation calculation was performed results in the obtained and showed the values in 4th decimal, which indicate that there isn't significant variability in their values.

The results illustrate the typical effect of the DBL on the jet penetration, in which the configurations with smaller DBL got greater jet penetration. The smaller DBL implies that the nozzle is closer to the metallic bath. This practice reduces the losses of the kinetic energy caused by jet degradation in the LD converter environment. Besides, it was noted the top flow rate is another important factor to benefit jet penetration. The high top flow rates allow an elevated transfer of kinetic energy to the metallic bath, which enhances the jet penetration. The bottom-blowing flow rate is also an essential variable to benefit the jet penetration. However, the relationship between the positions of the air jets of the Lance about the position of the tuyeres plumes must be taken into account. Depending on this relation, the bottom blowing can increase or reduce the jet penetration if the bath and jet velocity profiles are in the same sense or opposite senses (collision).

Another interesting analysis in figure 7 evaluates the nozzle number influence on the jet penetration. The increase of the nozzle number reduced the average jet penetration in the metallic bath. This effect is due to differences in the design of the nozzles. Notably, the increase of the nozzle angle with the vertical, θ, was the influence factor.

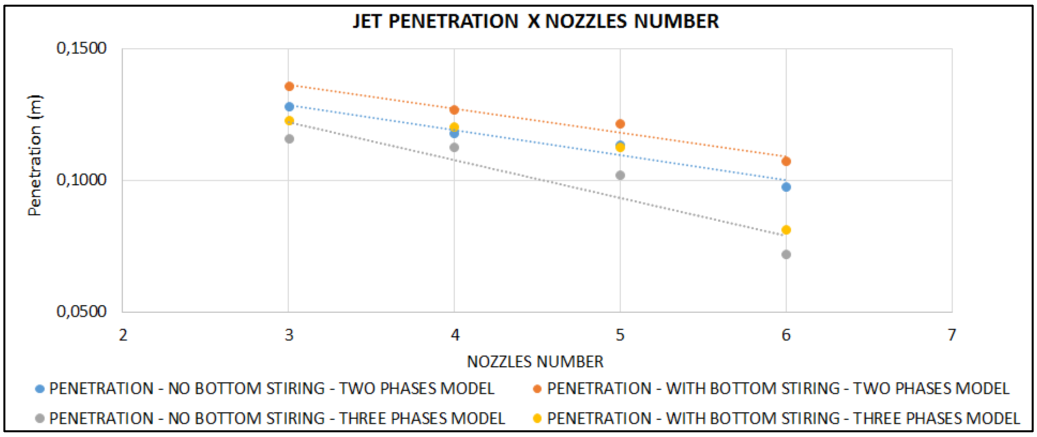


Figure 7 Jet penetration x Nozzles number in two and three models

3.2 Calculating the Compensation factor "K" by equation developed

Adjusting equation 18 to obtain the "K" values we have:

$$K = \sqrt{\frac{\pi}{27} \cdot \frac{Z}{\mathrm{Fr}^*} . \left\{\cosh\left[3.\operatorname{acosh}\left(\frac{3}{2}\mathrm{P}^* + 1\right)\right] - 1\right\}} \qquad [19]$$

Applying the jet penetration values obtained in the cold model in equation 20 the "K" values obtained were and shown in table VI.

Table VI – "K" values obtained

Nozzles Number	$K_{\text{Two Phase model}}$	$K_{\text{Three Phase model}}$	Nozzles Number	$K_{\text{Two Phase model}}$	$K_{\text{Three Phase model}}$
	No Bottom Stiring	No Bottom Stiring		With Bottom Stiring	With Bottom Stiring
3	1,8	1,7	3	1,4	1,3
4	1,7	1,6	4	1,3	1,3
5	1,6	1,5	5	1,3	1,2
6	1,5	1,2	6	1,2	1,0

A hypothesis test was performed were noticed that the values are statistically different and comparing the different models studied a small variation value was noticed. Both conditions allow simplifying these values in a unique value. Table VII show this value, which can be used in industrial mathematical models.

Table VII - Industrial “K” value

$K_{industrial}$	Standard deviation
1,4	0,26

3.3 The developed equation in comparison with the other authors jet equation published in the literature

A comparison was made between the equation developed in this work (equation 20) with that of Maia et al.[6] (equation 21) in order to evaluate the response of jet penetrations.

$$\mathrm{Y} = \frac{2}{3} \cdot \cosh\left\{\frac{1}{3} \cdot \mathrm{acosh}\left[1 + 27 \cdot \frac{\cdot \mathrm{K}^2}{\pi} \cdot \frac{\mathrm{Fr}^*}{\mathrm{Z}}\right]\right\} \quad [20]$$

$$\frac{\pi}{2 \cdot K^2} \cdot \frac{P}{DBL} \cdot \left(1 + \frac{P}{DBL}\right)^2 \cdot \left[1 + \left(\frac{P}{DBL}\right)^{-2} \cdot \frac{\cos\theta \cdot (\sigma_{STEEL} + \sigma_{SLAG})}{(\rho_{STEEL} + \rho_{SLAG}) \cdot g \cdot DBL^2}\right] = \frac{\pi}{4} \cdot \frac{\rho_{GAS} \cdot (V_{EXIT} \cdot D_{EXIT} \cdot \cos\theta)^2 \cdot n}{(\rho_{STEEL} + \rho_{SLAG}) \cdot g \cdot DBL^3} \quad [21]$$

The equal operational parameters were adopted as premises. The DBL values were extrapolated starting from a lance positioned at 6.0m and ending at 0.05m from the static bath. This extrapolation is illustrated in figure 8 and had the objective of verifying the behavior of the equations in the answer of the penetration values in each one of the equations.

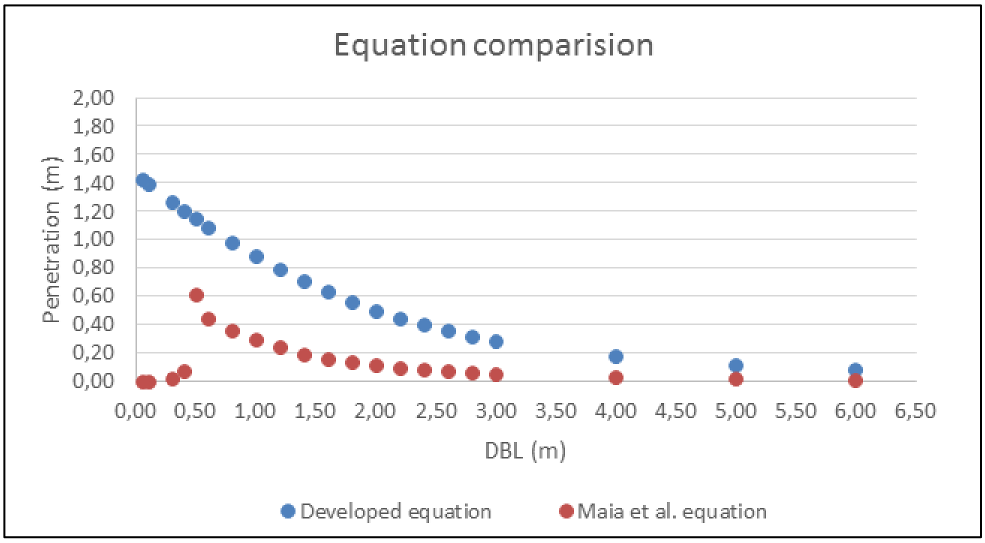


Figure 8 Equation comparison

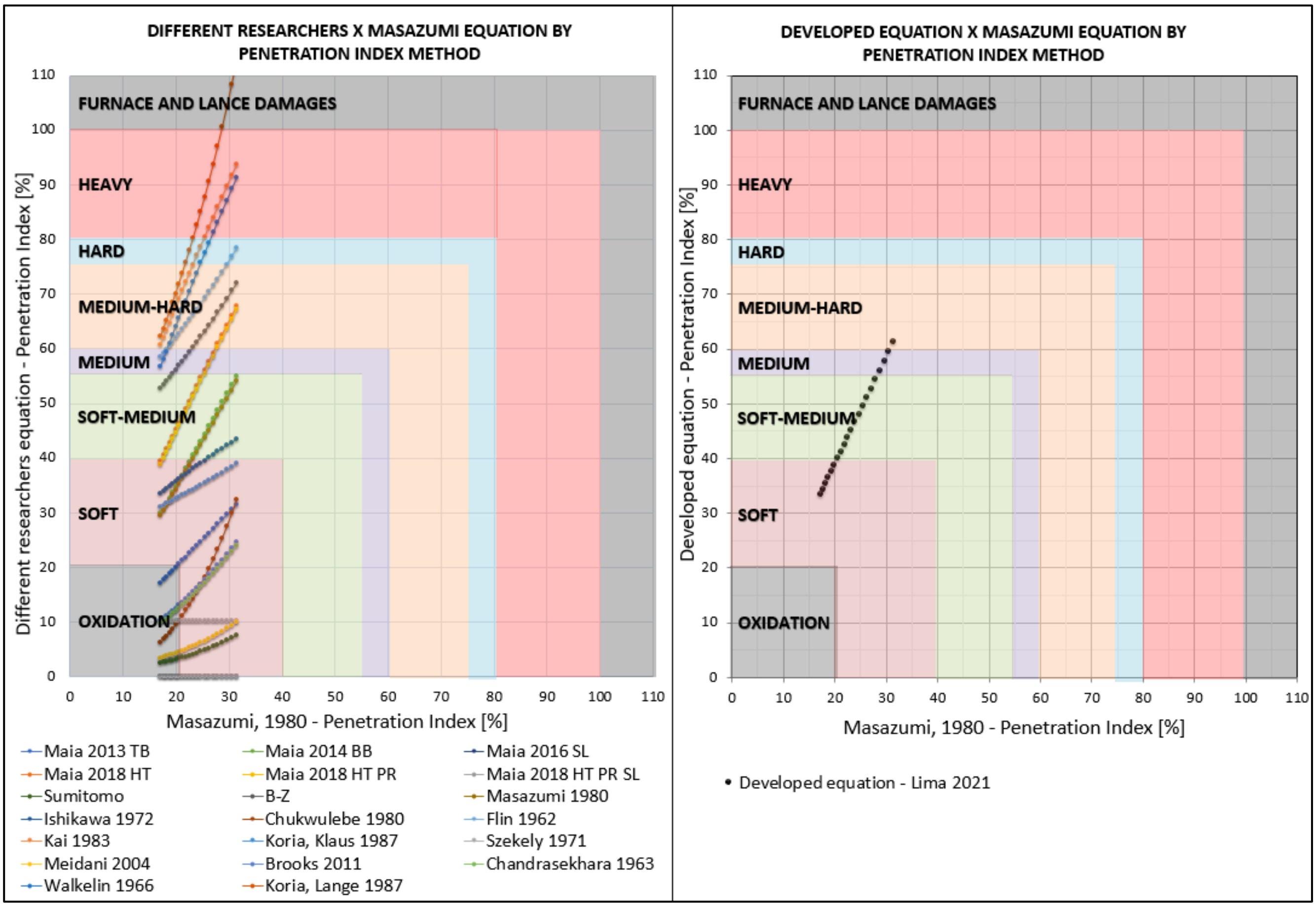
The vertical axis illustrates the jet penetration values while the horizontal axis the DBL values. Is noticed the behavior uniform the developed equation compared with Maia et al.[6] equation. It is important to note that Maia et al.[6] the equation does not show good convergence with lances positioning at distances below 0.80 m. It’s not so good due to the limiting the equation for some applications such as Slag Splashing and Bottom Burn which are necessary DBL less than 0.80m. The Maia et al.[6] equation showed some failures in their development which were fixed by the developed equation in this paper by Lima[30].

This time another comparison was made through the theoretical penetration index created by Balajee, et al. [31]. This index evaluates the kind of blow by the jet penetration. The analysis will compare the jet penetration equation developed with other researchers by the index penetration L/L_0. This is a theoretical model developed to provide a better understanding of the physical effects happening in a lance oxygen-blowing vessel and combines the effects of flowrate changes and lance movements (lance tip nozzle design differences included). Table VIII shows the index penetration definition by Balagee et al. [31].

Table VIII - Jet Penetration Effect on Blowing Behavior

TYPE OF BLOW	L/LO	BLOW ASPECT
Oxidation	<0.20	Oxygen jet doesn't touch the static liquid bath, just creates atmospheric oxidation into the vessel
Soft	0.20–0.40	Small penetration
Soft-medium	0.40–0.55	Jet penetration is enough for ignition; able to start Fe oxidation and lime dissolution
Medium	0.55–0.60	Penetration applied to some De-C conditions for low P. Foaming slopping occurs in this range.
Medium-hard	0.60–0.75	Penetration applied in general during De-C blow period
Hard	0.75–0.80	Strong penetration, normally for fast De-C time. Metallic slopping occurs in this range.
Heavy	0.80–1.00	This relation is used to blow fast and save time; avoids bottom buildup. Dangerous for lance tip.
Furnace and lance damage	>1.00	This range is used for specific works outside the blow, like the burning bottom

For the result, comparison of the equations of the different researchers and the actual developed, the equation of Masazumi [23] was chosen for reference because this is the common equation used in many BOF shops in North and South America. Figure 9 illustrates the result obtained. For both cases, the DBL values were considered traditional values applied to big converters in the industry, where starting from a lance positioned at 3.3m and ending at 1.8m from the static bath.



a) b)

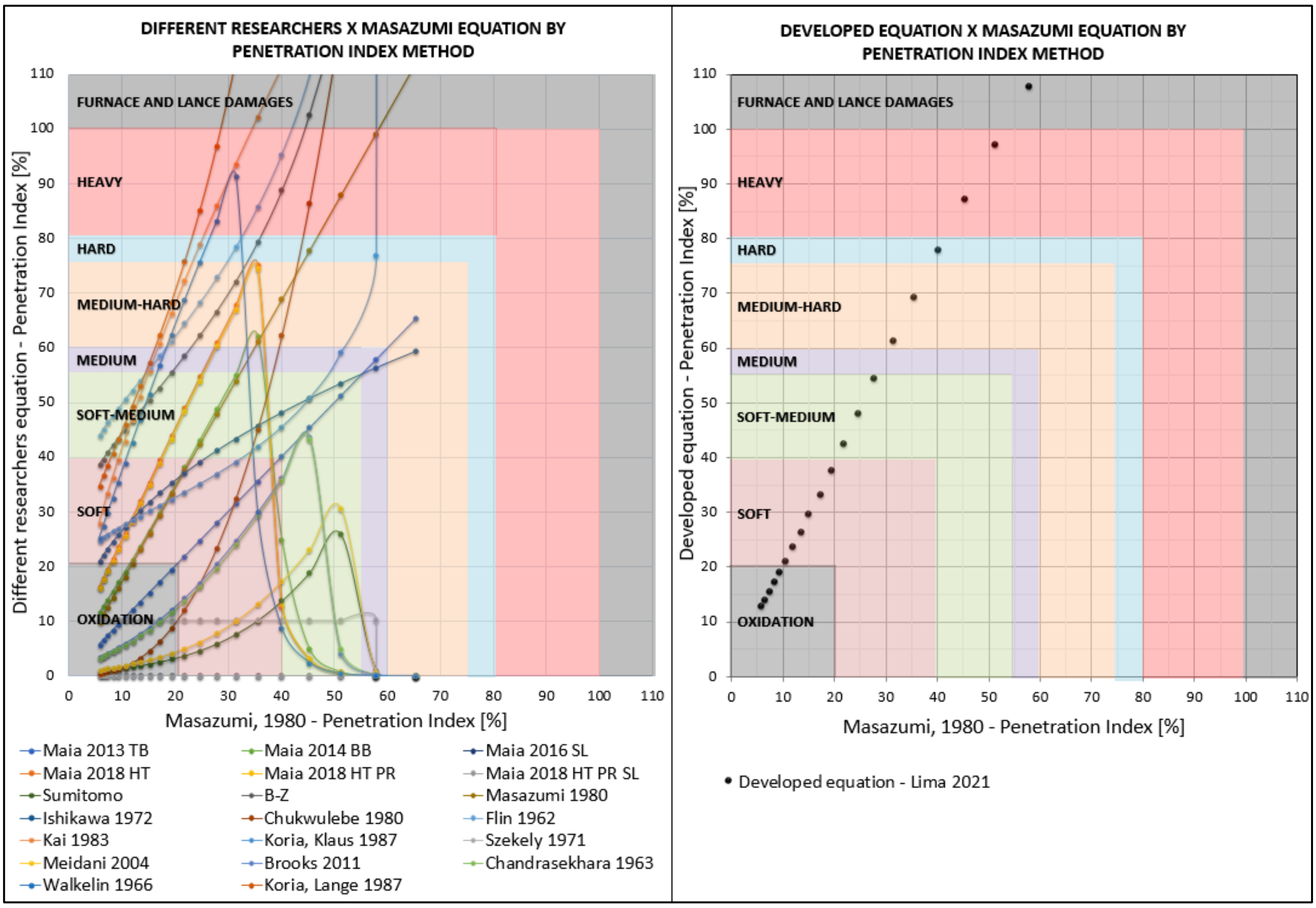
Figure 9 Comparision equation by the penetration index method – a) different researchers x Masazumi[23] b) developed equation by Lima[30] x Masazumi[23]

In figure 9a, on the horizontal axis, Masazumi's equation is fixed and on the vertical axis, the equations of different authors. In figure 9b the vertical axis was fixed the developed equation. The conditions and variables used in the equations to obtain the jet penetration values were applied equally among all authors. In the graph, the penetration index equivalence areas are marked.

In the figure 9 analysis, it is can be associated that the different results have a relationship with the industrial parameters used or not during developing their equation, besides the constants considerate or not.

This is possible to say because the different results were obtained, although were used the same value in all equations. Figure 9b showed there was good comportment in this equation. At the beginning of the blowing, it reached a small penetration allowing the ignition and slag formation, at the end of the blowing an efficient jet of oxygen in the decarburization, without reaching the bottom of the converter.

In figure 10 the DBL values were extrapolated starting from a lance positioned at 6.0m and ending at 0.05m from the static bath for both cases. The main objective was to evaluate the equation behavior in extreme situations.



a) b)

Figure 10 Comparison equation by the penetration index method with extrapolated DBL – a) different researchers x Masazumi[23] b) developed equation by Lima[30] x Masazumi[23]

It can be noticed that most of the equations of the different researchers presented problems of convergence for small DBLs.

However, their equations have a range of validity. It is generally observed that lance height values tending to fractional values are influenced by terms raised to the second and third power, being responsible for the divergence of calculated values and losing meaning compared to industrial practice. The equation developed in the present work corrects this problem, being able to attend the small distances from lance to the bath.

3.4 Industrial application proposal to the developed equation

The industrial application objectively compare the developed equation [22] by Lima[30] with Masazumi[23] equation [23]. Operational data was used of the 340t converter and applied in these equations respectively. Table IX shows these values.

Table IX Industrial data of the 340 LD converter

Blow time (%)	DBL (m)	Oxygen Pressure (kgf/cm²)	Oxygen Flow (Nm³/min)	N2 Flow (Nm³/min)	AIR Flow (Nm³/min)
1	3,2	15,7	930	3600	-
5	3,2	15,7	930	3600	-
10	3,2	15,7	930	3600	-
15	3,2	15,7	930	3600	-
20	3,2	15,7	930	18000	-
25	3,2	15,7	930	18000	-
26	3,0	15,7	930	18000	-
26	2,9	15,7	930	18000	-
27	2,7	15,7	930	18000	-
28	2,5	15,7	930	25200	-
29	2,2	15,7	930	25200	-
50	2,2	15,7	930	25200	-
60	2,2	15,7	930	25200	-
65	2,2	15,7	930	25200	-
70	2,2	15,7	930	25200	-
75	2,2	15,7	930	25200	-
80	2,2	15,7	930	-	25200
85	2,2	10,7	655	-	25200
90	2,2	20,6	1200	-	25200
95	2,2	20,6	1200	-	25200
100	2,2	20,6	1200	-	25200

$$P^{*} = \frac{2}{3} \cdot \cosh\left\{\frac{1}{3} \cdot \operatorname{acosh}\left[1 + 27 \cdot \frac{\cdot K^{2}}{\pi} \cdot Fr^{*}\right]\right\} - \frac{2}{3} \quad [22]$$

$$L = L_h * \exp(-0{,}78h/L_h) \quad [23]$$

Assim:

$$L_h = 63{,}0 * (k^* F_{O2}/n^*d)^{2/3} \quad [24]$$

The obtained result is illustrated in figure 11.

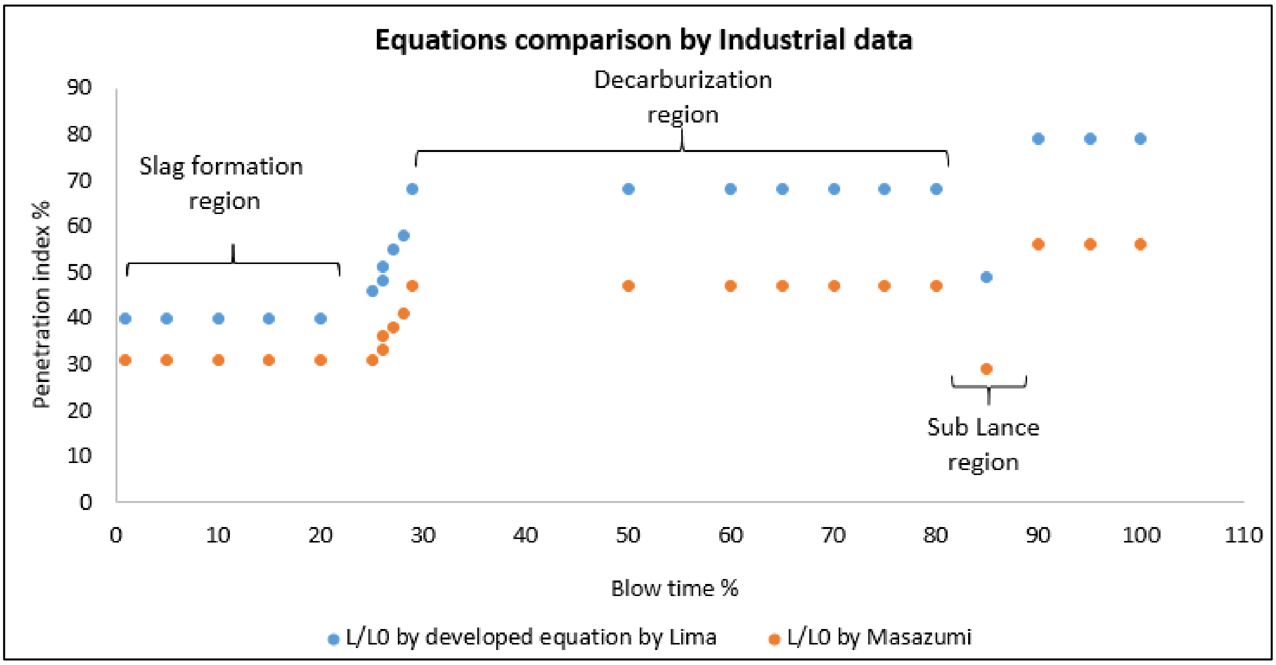
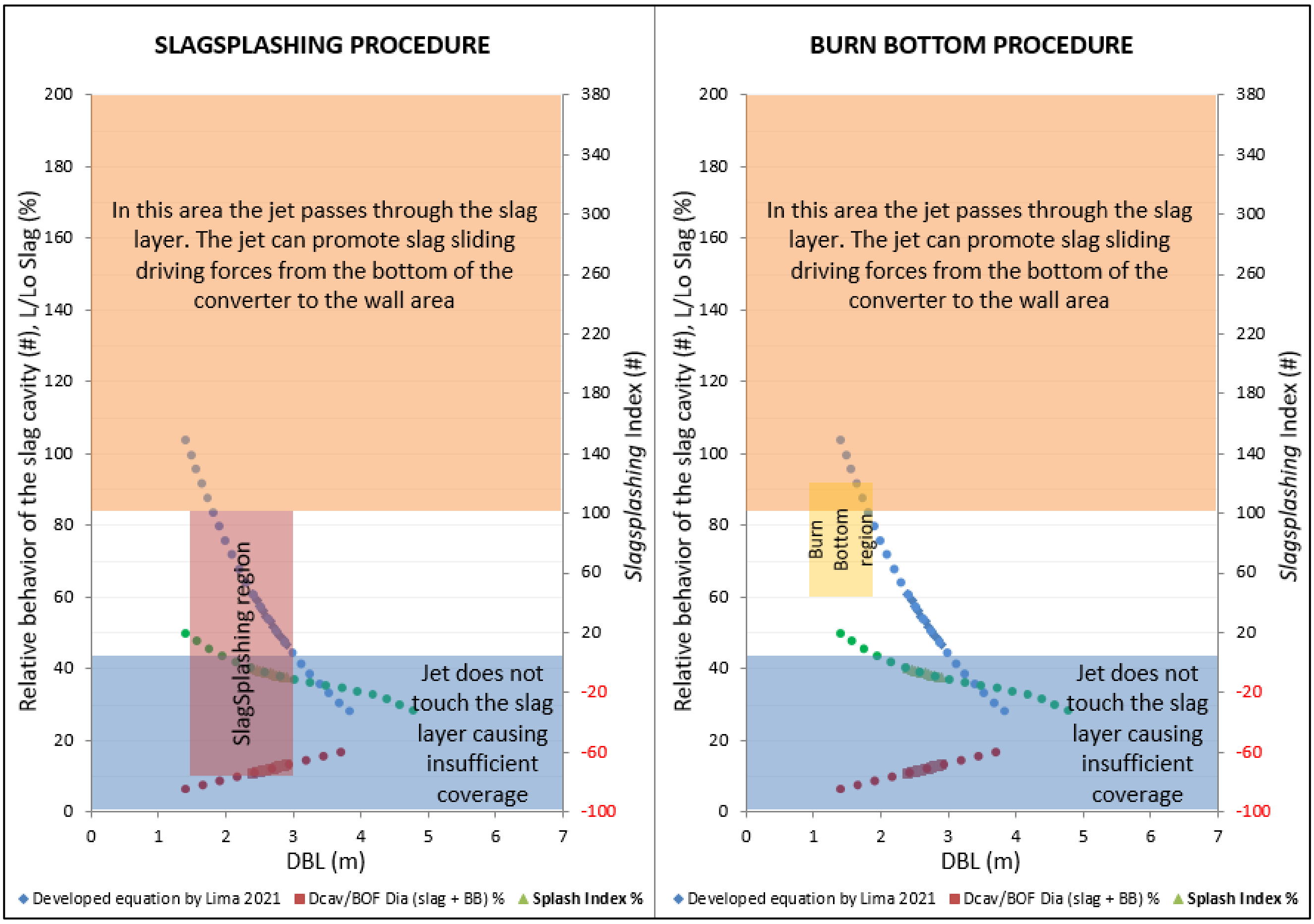


Figure 11 Equations comparison by Industrial data

Figure 11 the vertical axis shows the penetration index when horizontal axis the blow time. The blue point shows the developed equation and the orange point is the Masazumi [23] equation. It can be seen in the figure that the equation developed obtained an increase of 23% on average in the L/L_0 ratio compared to the one proposed by Masazumi [23].

The increase in jet penetration in the bath provides a reduction in blowing time, increasing the productivity of the converter. The difference between the results of the equations may be due to Masazumi[23] not having applied in his equation important process variables that influence the jet penetration, such as the slag layer, bottom blow information, and variation of the density bath during the blow. The equation proposed in this study considers these variables by adding a greater number of parameters that influence the greater or lesser jet penetration.

Another proposal of the developed equation application was made, this time the Slagsplashing and Burn Bottom procedure was created. It is important to create tools that allow a previous analysis of the procedure before the execution; this new proposal objective is to allow this condition of analysis. Figure 12 illustrates these new procedures.



a) b)

Figure 12 Procedures to analysis proposed – a) Slagsplashing proposal b) bottom burn proposal

The green line in Figure 12 represents the Slagsplashing Index, which represents the relationship between jet penetrations into the slag versus the cavity opening on the slag surface. As the lance advances towards the slag, the projected area over the slag surface reduces, and jet penetration increases. The right vertical axis represents the scale and the values range from positive to negative. Positive values represent greater extensions of slag volume projected by the jet on the walls of the converter and negative values represent the low volume of projected slag.

The blue line represents the jet penetration about the height of the slag layer available for Slagsplashing. Values greater than 100 mean that the jet is capable of penetrating beyond the slag layer, which is, reaching the refractories. This result is interpreted as the ability of the jet to push the slag towards the base of the converter towards the regions of the sole with the lower cone potentially up to the converter cylinder.

The red line represents the total area of the cavity formed by the impact of the jet on the surface of the slag about the diameter of the converter, allowing high lance heights to project large surfaces onto the slag, as this area is reduced, consequently increasing the jet penetration.

The red frame in Figure 12a represents the recommended area for slag splashing. On this occasion, the Slagsplashing index is arbitrate between 0 and 100.

The orange frame in Figure 12b represents the recommended area for the burn bottom. On this occasion, the Slag splashing index is arbitrated between 50 and 110.

The blue frame represents the jet projection area, which in general has a large projection diameter promoting little or no jet penetration, this region is the lower limit of the Slag splashing Index.

The pink frame represents the jet penetration greater than 100%, where the jets passes through the slag layer to reach the converter refractory. In these calculations, the restriction created by the refractory was not imposed. Such quantification was used to estimate the slag mass that the jet can displace from the base of the converter to the lower cone and cylinder region.

In general, the equation developed by the present study allowed the elaboration of the standards for the practices of Slag Splashing and burn bottom, which will allow the engineers of metallurgical processes of the Steel Plants a preliminary analysis before the application of the practices to the mathematical model.

4 CONCLUSION

In this study, jet penetration impingement on the two-phase and three-phase liquid baths (oil and water) were studied experimentally and theoretically, like the study on the jet penetration equation and the compensation factor "K", an influent term of this equation. The following conclusions can be drawn from this work.

1. Parameters most influential in the greater penetration of the jet: a smaller number of nozzles, smaller DBL, larger airflow, use of submerged blowing;
2. The oil layer acted with a resistance to the jet, thus reducing its penetration into the bath;
3. The momentum balance equation was developed and based on the cubic depressed resolution method, as it allows only one real root as an answer. This property made the solution method without the risk of computing a solution without physical meaning, which could occur if the equation had multiple real roots;
4. Applying the penetrations obtained in the new K equation, their mean values were extracted: 1.6±0.2 and 1.3±0.1 (Two-phase without and with bottom blow) and 1.5±0.2 and 1, 2±0.1 (Three-phase without and with bottom blow);

5. The industrial "K" value was proposed in 1.4 and can be applied in a mathematical model applied to LD converters;
6. Compared to other researchers' equations, the developed equation by Lima 2021 showed good behavior on the penetration results over a wide lance height range. The new calculation methodology can be applied in conditions other than blowing, such as slag splashing and bottom blowing practices;
7. Proposals for industrial applications were made using data from a 340t converter. Assessing the blow profile, the developed equation promoted the increase of the average jet penetration in 23%, compared with the equation of Masazumi[23]. The second proposal was to create a practical Slagsplashing pattern, which allowed a preview analysis before the real application. The third proposal consisted of creating a background blow profile, which will allow a preliminary analysis of the practice, allowing the visualization of the results before their application in the mathematical model. The preliminary analysis will allow the practice to be evaluated and carried out safely, reducing the risk of accidents.
8. The equation proved to be efficient for the various lance heights (positioned at lower to higher lance heights). It allowed the equation can be applied in another process besides the LD converter.

Acknowledgments

The authors would like to thank Lumar Metals for encouraging research and development, CNPq, FAPEMIG, CAPES, and PROEX CAPES for supporting PPGEM/UFMG.

This article is dedicated to Prof. Dr. ROBERTO PARREIRAS TAVARES, for his tireless work in training metallurgist engineers, dedication to perpetuation and knowledge generation. Owner of an unparalleled didactics, discipline in the conduct of developments and always able to coordinate those of good will.

REFERENCES

1. BANKS R. B., CHANDRASEKHARA DV., "Experimental investigation of the penetration of a high-velocity gas jet through a liquid surface". J Fluid Mech Jan. 1963; 15(1):13 and 34.
2. LI, M., LI, Q., KUANG, S., ZOU, Z.: "Numerical Simulation of the Interaction between Supersonic Oxygen Jets and Molten Slag–Metal Bath in Steelmaking BOF Process", Proceedings Metallurgical and Materials transactions B, 2015.
3. SZEKELY, J. THEMELIS, N. J.: "Rate Phenomena in Process Metallurgy", 1 ed. Montreal: John Wiley & Sons, 1971. 784p.
4. MEIDANI, A. R. N., ISAC, M., RICHARDSON, A., CAMERON, A., GUTHRIE, R. I. L.: "Modeling Shrouded Supersonic Jets in Metallurgical Reactor Vessels", Proceedings ISIJ International, 2004, v.44, n.10, p. 1639-1645.
5. ALAM, M., M.: "Modelling of Oxygen Injection and Splashing in Steelmaking", Thesis, Faculty of Engineering and Industrial Sciences Swinburne University of Technology, Melbourne, Australia, 2012.
6. MAIA, B. T., DINIZ, C. N. A., PEREIRA, G. G., SALGADO, R. S., TAVARES, R. P. "Determinação da massa movimentada em modelo a frio do banho metal escoria por sopro supersônico de bicos multifuros", ABM, 47 Seminário Internacional de Aciaria, 2016.

7. ISHIKAWA, H., MIZOGUCHI, S., SEGAWA, K.: "A Model Study on Jet Penetration and Slopping in the LD Converter", Proceedings Iron and Steel 1972, 76 – 84.
8. FOLSOM, R. G., FERGUSON, C. K.: "Jet mixing of two liquids", Proceedings Transactions of the American Society of Mechanical Engineers 1949, 71 – 73.
9. BANKS. B., CHANDRASEKHARA, D. V.: Proceedings Journal Fluid Mech 1963, 13-15.
10. DOGAN, N.: "Mathematical Modelling of Oxygen Steelmaking", Thesis, Faculty of Engineering and Industrial Sciences Swinburne University of Technology, Melbourne, Australia, 2011.
11. ALAM, M., IRONS, G., BROOKS, G., FONTANA, A., NASER, J., Inclined Jetting and Splashing in Electric Arc Furnace Steelmaking. ISIJ International, 2011, v.51, n.9, p. 1439-1447.
12. SEGAWA, K.: Proceedings Nikkan Kogyo Shimbun, 1977, 91-97.
13. FLINN, R. A., PEHLKE, R. D., GLASS, D. R., HAYS, P.O.: "Jet Penetration & Bath Circulation", Proceedings Transactions of the Metallurgical Society of the American Institute of Mechanical Engineering, 1967, 1176p.
14. KORIA, S.C., LANGE, K.W.: "Penetrability of impinging gas jets in molten steel bath", Proceedings Steel Research, 1987, v. 9, 421–426.
15. QIAN, F., MUTHARASAN, R., FAROUK, B.: "Studies of Interface Deformations in Single- and Multi-Layered Liquid Baths Due to an Impinging Gas Jet", Proceedings Metallurgical and Materials transactions B, 1996, v.27B, 911-920.
16. CHUKWULEBE, O.B., BALAJEE, S.R., ROBERTSON, K.J., GRATTAN, J.G., GREEN, M.J.: "Computer Optimization of Oxygen Blowing Practices to Control BOF Slopping", Proceedings AISTech, 2004, 751-762
17. PARK, S. S., DYUSSEKENOV, N., SOHN, and H.Y.: "The Penetration Behavior of an Annular Gas–Solid Jet Impinging on a Liquid Bath: Comparison with a Conventional Circular Jet", Proceedings Metallurgical and Materials transactions B, 2010, v.41B, 51-62.
18. LI, M., LI, Q., KUANG, S., ZOU, Z.: "Determination of Cavity Dimensions Induced by Impingement of Gas Jets onto a Liquid Bath", Proceedings Metallurgical and Materials transactions B, 2016, v.47B, 116-126.
19. ALBERTSON, M.L., DAI, Y.B., JENSEN, R.A., ROUSE, H.: Proceedings Trans. ASCE, 1950, v. 115, p. 639-45.
20. DAVENPORT, W. G., WAKELIN, D. H., BRADSHAW, A. V.: Proceedings of Symposium on Heat and Mass Transfer in Process Metallurgy, IMM, 1966, p. 207.
21. WAKELIN, D. H. Ph. D. Thesis, Imperial College, University of London, London 1966.
22. MEIDANI, A. R. N., ISAC, M., RICHARDSON, A., CAMERON, A., GUTHRIE, R. I. L.: "Modeling Shrouded Supersonic Jets in Metallurgical Reactor Vessels", Proceedings ISIJ International, 2004, v.44, n.10, p. 1639-1645.
23. MASAZUMI (Nippon Steel Corporation): "Converter steelmaking process" European Patent specification No. 0017963 B1, 15.04.1980.
24. MAIA, B.T., Imagawa, R.K., Petrucelli, A. C., Tavares, R. P.: "Effect of blow parameters in the jet penetration by physical model of BOF converter", Journal of Materials Research and Technology,2014, 244-254.
25. KRUSKOPF, A.: "A 2D Axisymmetric Mixture Multiphase Model for Bottom Stirring in a BOF Converter", Proceedings Metallurgical and Materials transactions B, 2017.
26. KAMARAJ, A., MANDAL, G.K., ROY, G. G.: Correction to: Control of Slag Carryover from the BOF Vessel During Tapping: BOF Cold Model Studies. Metallurgical and Materials transactions B 50, 1529 (2019).
27. QUIYOOM, A., Golani R,. Singh V., Buwa, V. V.: "Effect of differential flow schemes on gas-liquid flow and liquid phase mixing in a Basic Oxygen Furnace", Elsevier Chemical Engineering Science 170 (2017) 777–789
28. XIAO, J., Yan, H., Liu, L. et al. Effect of Bath Depth and Nozzle Geometry on Spout Height in Submerged Gas Injection at Bottom. Metallurgical and Materials transactions B 50, 3002–3011 (2019)

29. SANTOS, I. A. S., Santos, V. R. M., Lima, W.R., Silva, A. L., Maia, B.T.:" Slag splashing: simulation and analysis of the slags conditions", Journal of Materials Research and Technology,2019.
30. LIMA, W. R., “Modelagem do fator de compensação “K” da equação de balanço de quantidade de movimento em banho metálico no LD” Dissertação de Mestrado, Engenharia de materiais e metalurgia, UFMG, PPGEM, Belo Horizonte.
31. BALAJEE, S., MAIA, B. T., TAVARES, R. P., CAPPEL, J., “Practical Approach of Penetration Index Equations for Use in BOF Blowing Pattern Design” Iron Steel Technology, April 2019, Pages 1-12.