

Available online at www.sciencedirect.com

jmr&t
Journal of Materials Research and Technology
www.jmrt.com.br



Original Article

Effect of blow parameters in the jet penetration by physical model of BOF converter

Breno Totti Maia^{a,*}, Rafael Kajimoto Imagawa^b,
Ana Clara Petrucelli^b, Roberto Parreiras Tavares^b

^a Lumar Metals Research, Santana do Paraíso, MG, Brazil

^b Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, MG, Brazil

ARTICLE INFO

Article history:

Received 16 January 2014

Accepted 16 June 2014

Available online xxx

Keywords:

BOF

Jet penetration

Froude number

Splashing

Nozzle

Lance

ABSTRACT

It is important to know about the bath behavior to reduce the blow time and splashing in top of the converter. The target of this work is to compare works on the effect of twisted nozzle, flow and lance height in the jet penetration by visual inspection and by energy balance that consider number of nozzles, vertical and twist angles. In the present work, lances with twisted nozzle angles, normal lances and special nozzle shape were used to describe the effects of jet on bath. Jet penetration and level of splashing were also available. For the four nozzles, the best result to reduce spitting was obtained at the twist angle, hard blow and high flow. High flow, reduction in bath lance distance and lower nozzle angle promoted a higher penetration, but with bad results for the process. The energy balance showed to be a proper tool to promote adjustments in process.

© 2014 Brazilian Metallurgical, Materials and Mining Association. Published by Elsevier Editora Ltda. All rights reserved.

1. Introduction

The BOF converter is a simple and unique equipment for steel production. For years, many developments have been added to the BOF in order to reduce the time of blow, the oxygen and phosphorus at the end of the blow and to increase the life of the refractory. In this sense the improvement of the blowing oxygen techniques is essential to reach new challenges that, in certain circumstances, can be antagonistic in their

main objectives, like for example remove phosphorus without increase the oxidation.

According to Glass et al. [1,2], in the point where the gas hits the liquid surface, a depression or cavity is formed, the surface becomes unstable and oscillates in both directions, lateral and vertical. The transfer of momentum of the gas jet causes circulation of the liquid bath and also causes rising edges around the depression. After a certain depth of depression, a small ripple, originates around the periphery and breaks into droplets, which are ejected into the environment when they return and

* Corresponding author.

E-mail addresses: breno.totti@lumarmetals.com.br, breno.totti@terra.com.br (B.T. Maia).

<http://dx.doi.org/10.1016/j.jmrt.2014.06.010>

2238-7854/© 2014 Brazilian Metallurgical, Materials and Mining Association. Published by Elsevier Editora Ltda. All rights reserved.

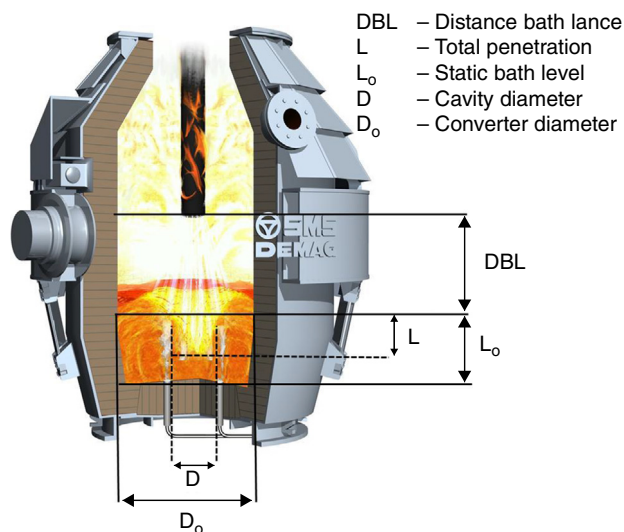


Fig. 1 – Bath deformation formed by the jet impact.
Adapted from Odenthal et al. [4].

drag small gas bubbles. This depression may be measured by two parameters, the depth of the depression measured from the center of the converter and the diameter of deformation in relation to the static bath as shown in Fig. 1, adaptation from Odenthal et al. [3].

This deformed surface is not stable, oscillating in the vertical direction cyclically and with rotations, as investigated in cold models [4–7]. The impact area of the blast into the bath, where oxygen reacts, has been called fire point, and there are studies showing temperatures in this region, around 2300 °C [8]. With the evolution of the blowing time, the foamy stage involves the blast, changing its characteristics in comparison to the beginning of refining. The depth of the depression in the bath liquid can be correlated with the amount of blast movement through an energy balance at the base of the cavity, according to the following equation, proposed by Szekely et al. [9]:

$$\frac{1}{2} \cdot \rho_{\text{outlet}} \cdot v_x^2 = g \cdot \rho_B \cdot H_c + \frac{2 \cdot \sigma}{r_c} \quad (1)$$

where ρ_{outlet} , density at the nozzle outlet (kg m^{-3}); ρ_B , bath density (kg m^{-3}); v_x , jet velocity below the tip outlet along the jet axis (m s^{-1}); g , gravity acceleration (m s^{-2}); H_c , height of the bath cavity or penetration (m); r_c , radius of the cavity in the bath at the stagnation point (m); and σ , surface tension (N m^{-1}).

According to Meidani et al. [4] if the viscosity and the surface tension are neglected, the blast penetration can be expressed in terms of the Froude dimensionless numbers function of the Froude number, as shown below.

$$\frac{P}{H} = f(\text{Fr}) \quad (2)$$

$$\text{Fr} = \frac{\rho_g \cdot \bar{V}_s^2 \cdot D_s^2}{\rho_l \cdot g \cdot H^3} \quad (3)$$

where P , penetration; H , distance between the lance and the bath to DBL; Fr , Froude dimensionless numbers; ρ_g , gas density; V_s , gas velocity in the nozzle outlet; D_s , diameter at the nozzle outlet; ρ_l , liquid density; g , gravity.

For each type of lance, an increase in Froude number implies an increase in the jet penetration. According to this theoretical analysis presented by Meidani et al. [4] the jet penetrating can be expressed in terms of the Froude number modified according to equation:

$$\text{Fr}^* = \frac{2}{K^2} \frac{P_j}{H} \left(1 + \frac{P_j}{H} \right)^2 \quad (4)$$

where K is an empirical constant for each type of lance.

The proposal of this paper is to compare the correlation between the main blow parameters: lance height or distance bath lance, flow, kind of tips and penetration and bath movement.

2. Methodology

The experiments were conducted in a physical model of the “Laboratório de Simulação de Processos” (LaSiP) of the School of Engineering at UFMG, as shown in Fig. 2, which represents a vessel of 220 t of steel.

For the experiments, the vessel was filled with water at the height that represents the level of the metal bath. At the compressed air system outlet the lance tips were connected. To feed the system with compressed air, a 22.5 kW compressor was used, capable of providing a maximum pressure of 7.87×10^5 Pa and a maximum flow of $189 \text{ m}^3/\text{h}$. The experiments obey the geometric and kinetics similarity recommended by Carneiro [10]. Fig. 3 shows the top and the side views with the difference between the tips.

In Fig. 3, the lance rotation angle 0° corresponds to standard nozzle (a). The nozzle with torsion angle θ is defined in Fig. 3(b). Axis of lance is at point “P”, inlet nozzle is at point “I” and output at point “O”. Point “J” is the nozzle projection axis over bath surface. In normal nozzle, the point “P”, input “I” and the output “O” of the nozzle are aligned, hence point “J” is also in the same alignment. In nozzle with torsion, point “J” is aligned with the input “I” and output “O”, not intersecting point “P”, it means, the center of lance. Thus, torsion angle is defined by intersection of two lines at point “O”, being the first line, determined between two exit nozzles going through the point “P” and the second line, the joining points “I”, input, and “O”, output, of one nozzle [11,12]. The second group of experiments was conducted comparing the effects of the angle to the vertical and the smoothing of the nozzle geometry, as shown in Fig. 4. It can be noted in parts (a) and (b) increase of the angle to the vertical spacing the nozzles to the other. In part (c) of Fig. 4 attention should be given to the internal geometry of the nozzle, consisting of a parabola which goes from the convergent section to the divergent section, with the aim to reduce the length of the straight segment of the critical diameter, as presented in detail in Fig. 5.

According to Maia et al. [13], the straight stretch in the throat region causes a decline in the efficiency of the

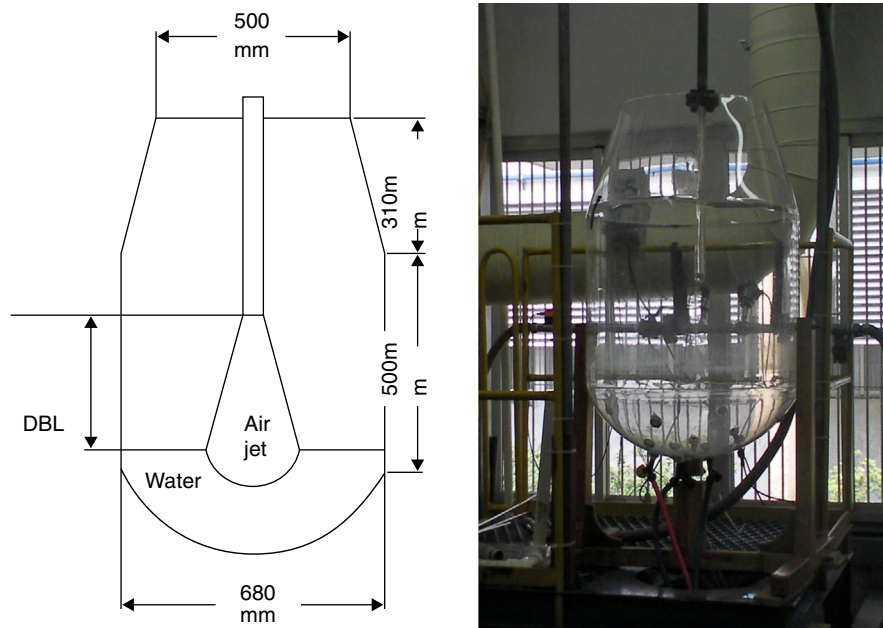


Fig. 2 – Dimensions of the BOF converter physical model.

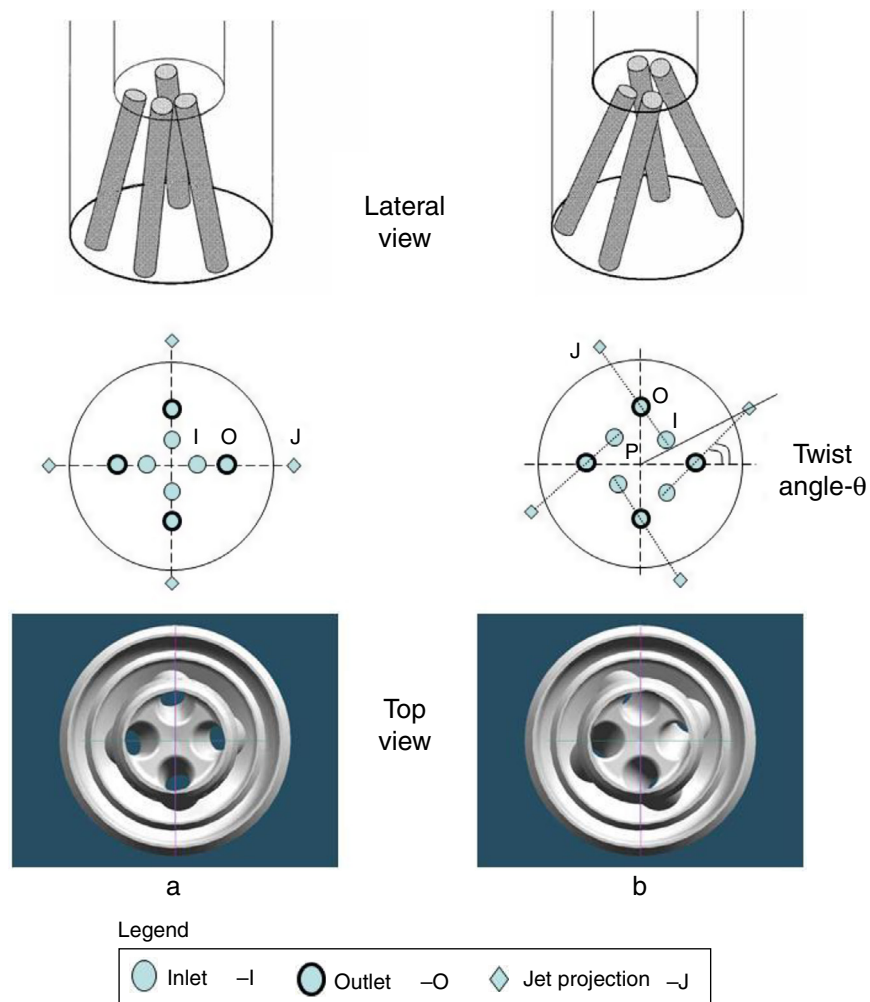


Fig. 3 – Comparison between (a) standard tip and (b) tip with torsion.

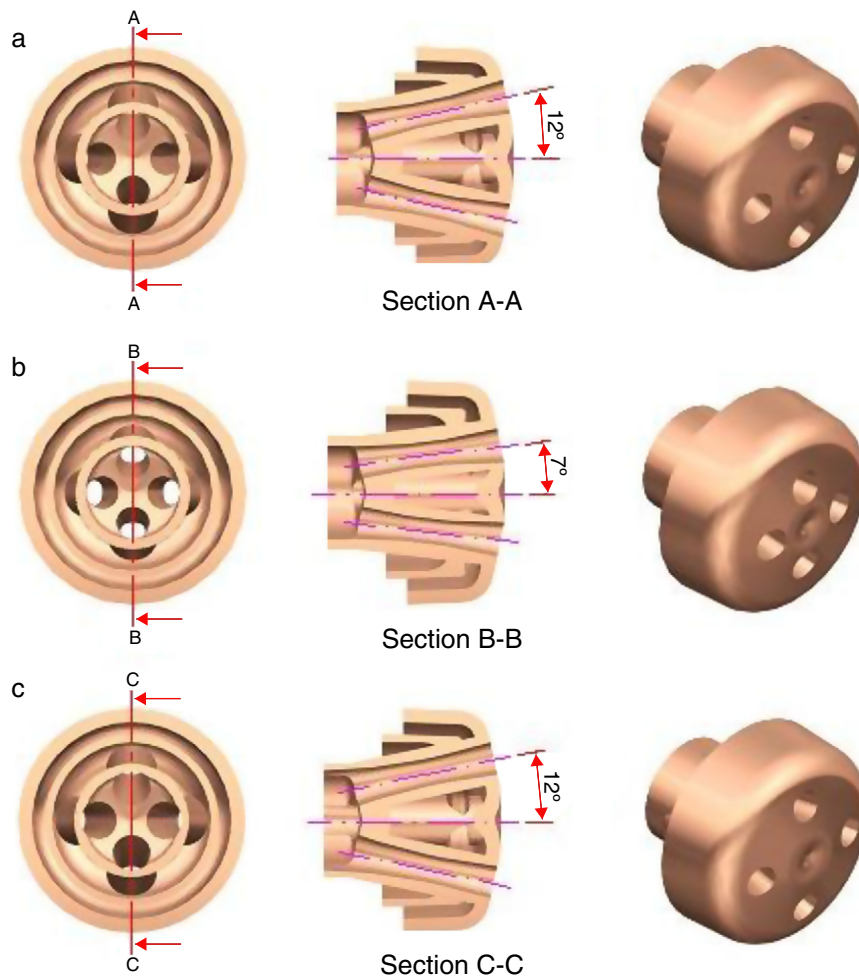


Fig. 4 – Comparison between (a) standard tip, 12° to the vertical and (b) standard tip 7° to the vertical, and (c) tip with softened nozzle and 12° to the vertical.

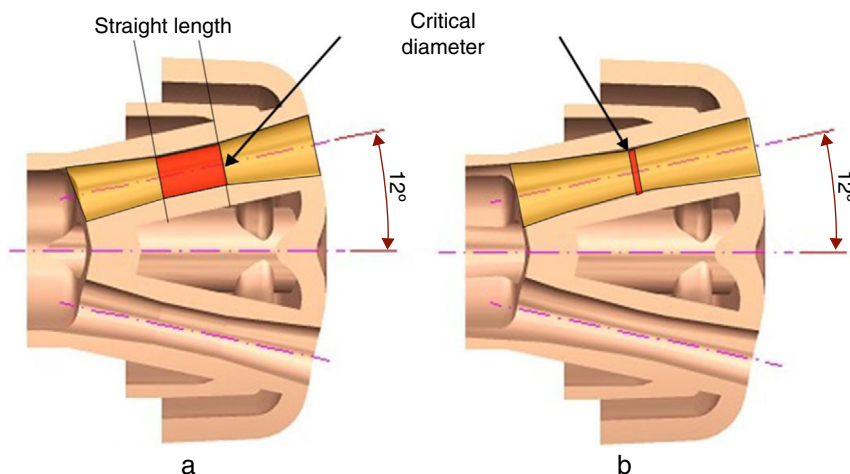


Fig. 5 – Details of the constructive difference between (a) standard tip with 12° to the vertical and (c) tip with softened nozzle and 12° to the vertical.

transition properties of the gas and consequently loss in penetration blast. The similarity between the gas speeds during the blowing can be demonstrated using the Mach number and the depth of the gas jet penetration is dependent

on the Froude, Reynolds and Weber numbers modified for the liquid, reflecting the relationship between the gravity force, viscous force and surface tension forces to the jet [10,14–16]. Table 1 shows comparison of values between dimensionless

Table 1 – Comparison between dimensionless numbers in the industrial reactor and the physical model of the BOF converter.

	Symbol	Unit	Description	Industrial	Physical model
Dimensionless numbers	Ma	#	Mach number	2.07	2.01
	Fr*	#	Froude modified	0.0357	0.04616
	Re*	#	Reynolds modified	7.19E+05	9.09E+04
	We*	#	Weber modified	4.399E+03	2.076E+03

Table 2 – Parameters varied in the tests with torsion.

Nozzle configuration	Height	Flow rate
Torsion 20	0.250 m	160 Nm ³ /h
Torsion 10	0.180 m	130 Nm ³ /h
Torsion 0	0.117 m	100 Nm ³ /h

Table 3 – Parameters varied in the tests with varying vertical angle.

Nozzle configuration	Height	Flow rate
7°	0.250 m	160 Nm ³ /h
12°	0.180 m	130 Nm ³ /h
12° softened	0.117 m	100 Nm ³ /h

numbers and the industry parameters and the parameters of the cold physical model.

Considering that the current tips have many holes and with varying angles, studies were made isolated [17–21], and it is necessary to incorporate these two variables, proposing a new equation, as shown in Eq. (5).

$$\frac{\pi \times \rho_g \times V_S^2 \times D_S^2 \times \cos \theta \times n}{4 \times \rho_l \times g \times H^3} = \frac{2}{K^2} \frac{P}{H} \left(1 + \frac{P}{H \times \cos \theta} \right)^2 \quad (5)$$

where θ , the resultant angle between the vertical and torsion; n , holes number.

Eq. (5) represents the energy balance between kinetic energy from the nozzles and mass movement into the bath.

The experiments were divided into two steps: one to evaluate torsion angle effects and other vertical angle effects. In both series the nozzle settings, lance heights and flow rate were changed and the jet penetration and bath movement were measured. Table 2 shows test parameters that attempt to evaluate the torsion effect. Tests with parameters shown in Table 3 evaluate the vertical effect.

3. Results and discussion

3.1. Evaluation of the torsion effect in the penetration and bath movement

Fig. 6 shows images of the converter with a lance height of 0.117 m, comparing the flow effects and configuration of the tip with torsion.

For all the flow conditions the tip with a 0° torsion, here called torsion 0°, showed the highest penetration, reaching the converter bottom. In practice, it may mean an increased wear on the BOF converter soles. This condition corresponds to the hard blow, where the lance is very close to the bath surface.

The behavior of tips 20° torsion and 10° torsion was similar, mainly influenced by the flow increase. However, there is a tendency of the tips with torsion to produce independent jets; this effect is more pronounced in torsion 20°.

For the height of 0.18 m the 0° torsion tip for all the flows produced jets that touched the converter bottom, the one with higher flow being the most intense. Again, the independence among the four jets with the tips with torsion was noticeable, as shown in Fig. 7.

Comparing the influence of the height 0.117 m, representing a hard blow due to the short distance to bath, and blow with 0.180 m, representing a normal operating condition, it is possible to notice the difference caused by the bath projection. For tips with torsion, the spreading of liquid above the level of the static bath to a height of 0.117 m is lower when compared to the height of 0.180 m. For the 0° tip with torsion, the effect of jet coalescence increases the bath projection, impinging mainly on the body of the lance. The images also indicate that jets with greater penetrating power, also provide a lower tendency to material project. Fig. 8 showed the effects of the distance bath lance equal to a 0.250 m on the bath.

For the tests performed with a height of 0.250 m, only the tip without torsion presented a jet able to touch the bottom of the converter. The tips with 10° torsion and 20° torsion for flows of 100 Nm³/h and 130 Nm³/h showed small penetrations compared to other height. In practice this configuration resembles the onset of the blow, where the lance is at a greater distance from the bath. This configuration would be bad for decarburization, but would produce a more oxidized slag, so being favorable to melt scrap in the blow beginning, the lime dissolution and dephosphorization.

As expected, the higher flow rates produce the larger penetrations, since the jets with higher velocities have greater kinetic energy. The increase in the distance between lance and bath also shows the decrease in the jet speed in relation to the outlet speed of the Laval. The configurations with the lower altitudes had higher levels of penetration. Both results are consistent with the literature [13,18–20]. The configurations of tip with a torsion presented a splash effect that are well distributed and less concentrated on the lance, tending to force the movement of the bath against the walls of the converter. The configuration without torsion presented splash concentrated on the lance area and with higher ranges of height, in practice this can lead to more frequent formation of skull on the lance, being necessary to stop the blow to remove the skull. Note that the effect of the use of tips with torsion should be evaluated on the walls of the converter relative to the refractory wear.

The energy balance calculation was made using Eq. (5). The penetration measurements were performed by filming each

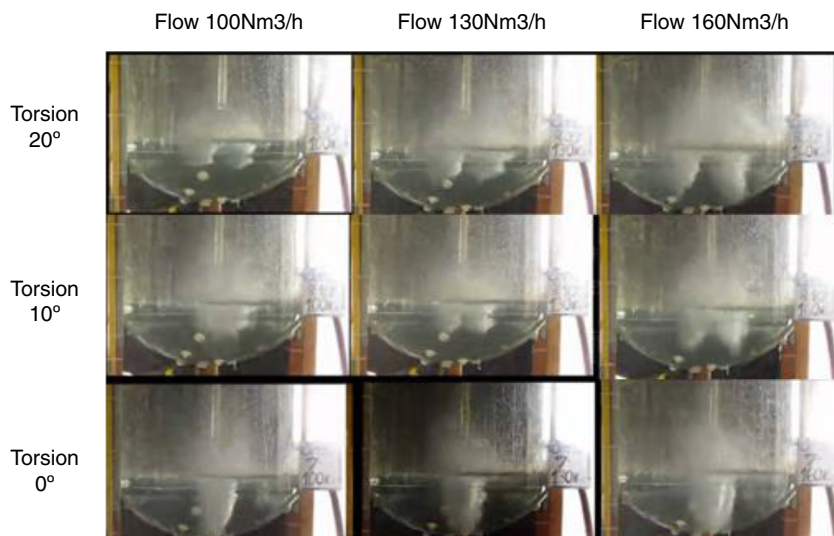


Fig. 6 – Images illustrating the jet penetration for a 0.117 m height comparing flow effects and configuration of the tip with torsion.

test. The recordings were started with the static bath then freed up the test flow, being filmed until the bath showed a monophasic character due to water turbidity caused by mixing with air. It was selected after an image that corresponds to maximum penetration and penetration depth now determined.

In Fig. 9, the abscissa represents the distance of the lance to the bath used in the experiments and in the ordinate the column of liquid corresponds to the difference of the initial column or static bath level subtracted from the value of penetration attained in each test. The measured values (black square) were obtained through the rehearsal footage. On occasions when the jet touched the bottom of the converter, the value of the liquid column was considered zero. In industrial terms, this means that potentially the refractory background converter will suffer premature wear. In terms of the values

calculated, this refractory aggression is attributed to negative values obtained in the graph. For tips with 0° torsion, in flows of 160 and $130 \text{ Nm}^3/\text{h}$ the incidence of the jet on the bottom of the converter for all the lance heights (0.117–0.180 to 0.250 m) occurred. Just for the $100 \text{ Nm}^3/\text{h}$ flow and 0.250 m height it was observed that the jet does not reach the bottom of the converter. For this case it is important to note that the two methods used showed approximate values of the liquid column.

Inserting torsion between the jets of 10° the jet penetration was reduced. It is observed in Fig. 10, a correspondence between the measured and calculated values, except when the jet reaches the bottom of the converter, especially for low value height lance and high flow.

With increase of the 20° torsion and the lower flow rates (130 and $100 \text{ Nm}^3/\text{h}$), there was a good representation of the values, as shown in Fig. 11.

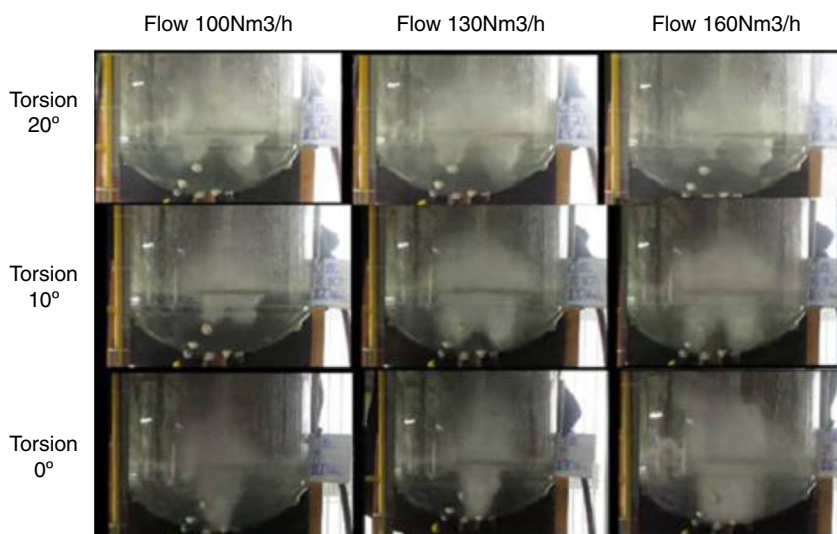


Fig. 7 – Images illustrating the jet penetration for a 0.180 m height comparing flow effects and configuration of the tip with torsion.

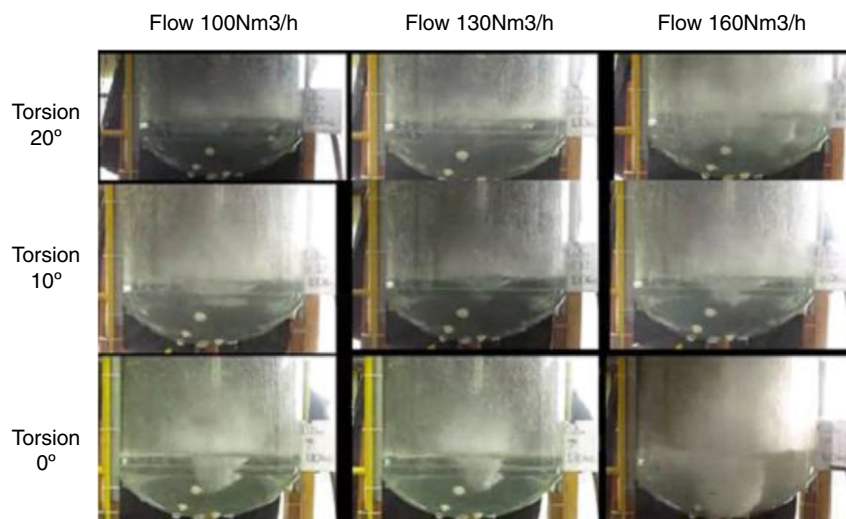


Fig. 8 – Images illustrating the jet penetration for a 0.250 m height comparing flow effects and configuration of the tip with torsion.

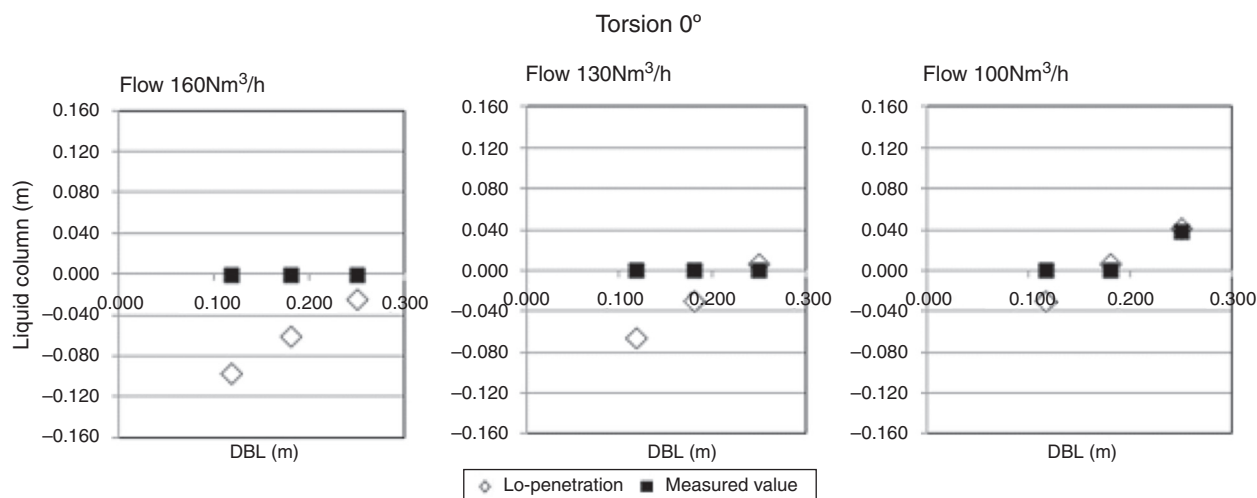


Fig. 9 – Flow × penetration with a 0° torsion tip.

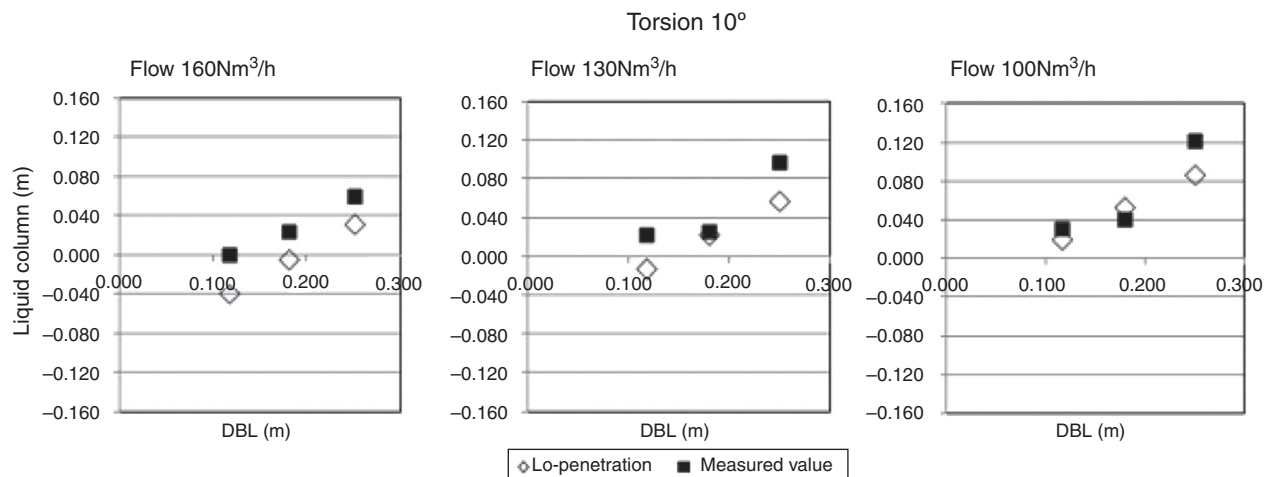


Fig. 10 – Flow × penetration with a 10° torsion tip.

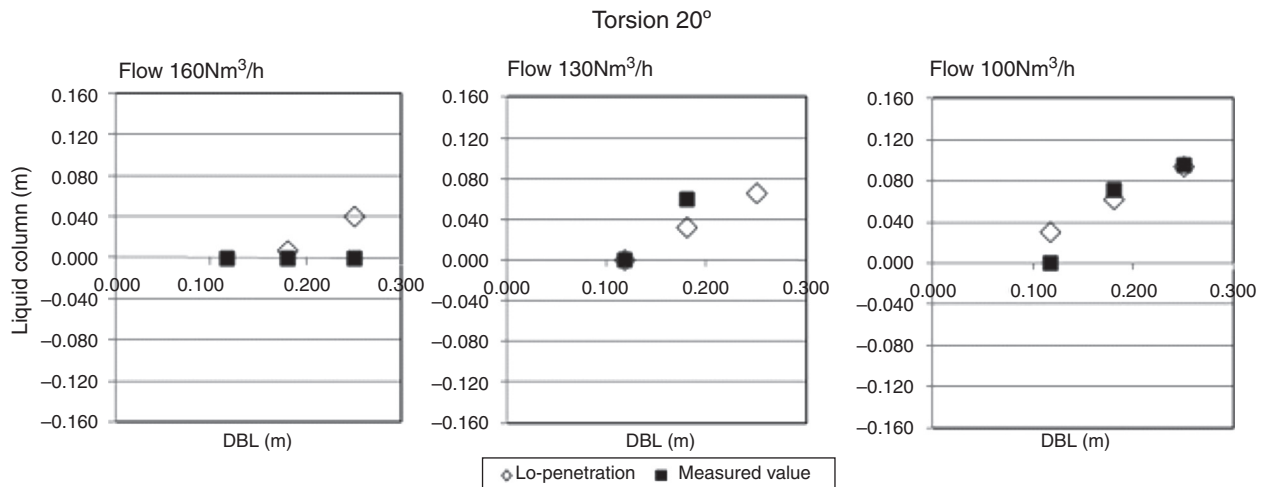


Fig. 11 – Flow $\times$ penetration with a 20° torsion tip.

The behavior of the 160 Nm³/h flow for the measured values was contrary to expectations, because in all circumstances the jet reached the bottom of the converter. From Eq. (5) and to tip with torsion type was generated a graph correlating the dimensionless penetration, term on the left side of Eq. (5) with the modified Froude number, and the right side of Eq. (5), as shown in Fig. 12.

From Fig. 9, it is possible to observe the trend of a straight line and thus it is possible to calculate the value of the K constant in Eq. (5). The calculation for determining the inclination of the line was performed using the free software Eureka Formulize. The results are presented in Table 4.

The K values presented in Table 4 are close to the values found by Maia et al. [13] in tests that were made using a 1:6 scale converter of the industrial reactor.

Table 4 – Value of the K constant for different torsion angles.

Tip type	K	R^2
0° torsion	5.72	0.99627603
10° torsion	4.63	0.99627503
20° torsion	4.62	0.99627557

3.2. Evaluation of vertical angle and geometry of the Laval in penetration and in the bath movement

Fig. 13, for height of 0.117, shows the penetration for the tests performed varying the angle of the tip relative to vertical and geometry of the Laval. The tip with angle of 7° showed coalescence of the jets, the behavior of independent jets not

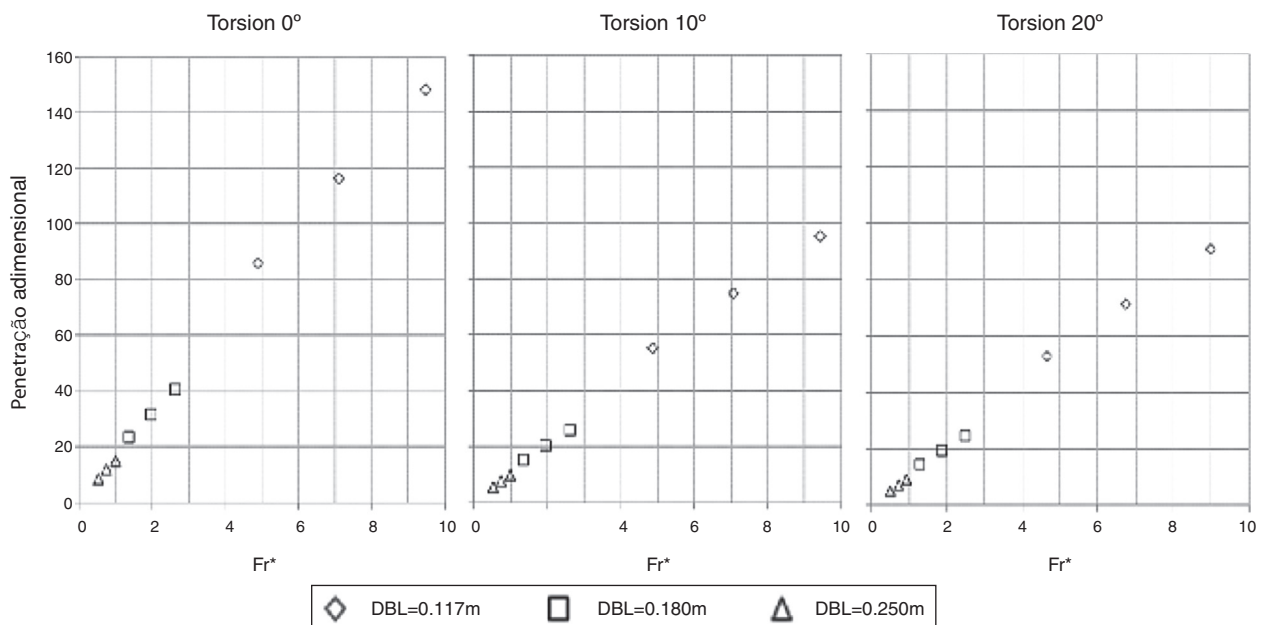


Fig. 12 – Dimensionless jets penetration $\times$ modified Froude for several lances height and torsion angles.

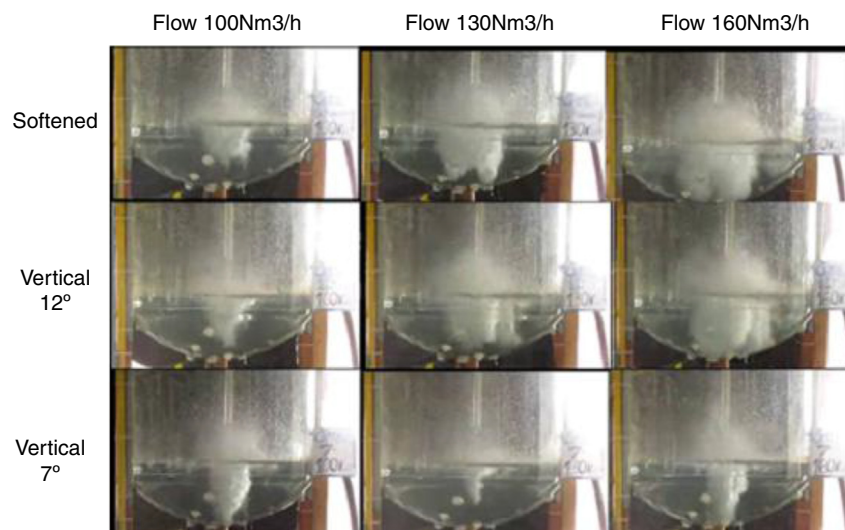


Fig. 13 – Images showing the jet penetration with a 0.117 m height comparing flow effects and tip configuration with an angle to the vertical.

being clearly perceived. For tips with larger opening, 12° and smoothed geometry, it is perceived in the same scale as the trend of “decoupling” of the four jets with an increase of the angle to the vertical. For all settings of the tip the jet touches the bottom of the converter, from the lower flow to the highest.

The jets of the test were performed at the height of 0.180 m to touch the bottom for the 7° and 12° tips and softened geometry only when flow is maximum, the jet has enough power to reach bottom. Again to 12° tips and with softened geometry there are separate jets, seeing that for greater flow, the effect is more evident, as shown in Fig. 14.

The mist formed can be compared to projections caused by jet impact on liquid metal concentrates preferentially in the region just below the lance, and this dense mist is denser when the flow is bigger. Thus, there is evidence that in industrial practice these types of tip can generate higher volume of spray on the lance and consequently increase of skull. This test must be done carefully, since the model represents only the behavior of the liquid metal charge, without being considered, however, the slag effect and temperature in the skull formation. Fig. 15 shows the behavior for the soft blow.

The lance height of 0.250 m presented a smaller jet penetration into the bath, though the jet of the 7° tip had penetration in the bath enough to touch the bottom converter. For the height of 0.250 m the effect of jet independence was less pronounced than for lower heights, in this case the interaction with the environment is crucial to the behavior of the jet. However when lance increasing height and increasing angle with the vertical is evident the increase of fog above the static bath line and in most images, covering body lance.

In summary, the tip of the lance with 7° to the vertical showed the highest values of penetration, and for all parameters of flow and lance height were able to touch the converter bottom, this tip was also the one to present a greater degree of coalescence of jets and through the filming was not possible to distinguish four jets separately.

All tips presented an area of fog that corresponds, in the industry practice, to projections of the liquid metal when in contact with the jet of oxygen. This zone appeared more dispersed and less dense for the tips with torsion effect. In the tips untwisted, this region was concentrated just below the lance and it was denser for higher flow rates. The presence of projections concentrated in the central region indicating that these types of tips can have disadvantages as favoring the formation of skull on the lance during blowing.

The tips with torsion, besides to reduce lance spray, promoted a stirring of the bath toward the walls of the converter. In these tips the formation of the independent jets was more effective, although this effect is observed on a smaller scale in the 7° tips and softened geometry. Once the jets are independent there is a great chance that the decarburization basin is larger and consequently more efficient to shorten the decarburization time in industrial processes.

During the experiments after some testing time the bath acquired counter clockwise rotation movement. This movement profile was observed for all combinations of tips, flow rates and height. However, in tests with tip with torsion, this movement profile was achieved with less time.

The analysis of the filming allows observing an interesting phenomenon that occurs when there is independence between the jets. Despite all the nozzles of the tips being at a same pressure, the fact that the gas flow is turbulent generates the alternation among the jets, which causes the effect that the jets hitting the bath surface have different energies. The jet flow affects the behavior of others, causing changes in the penetrations over time. This alternation between jets can be compared to cyclic pulses in which each moment of a jet nozzle has more kinetic energy.

Following the same method used for the tests with tip with torsion angle, the energy balance calculation was made using equation (5) and the jet penetration values were obtained from

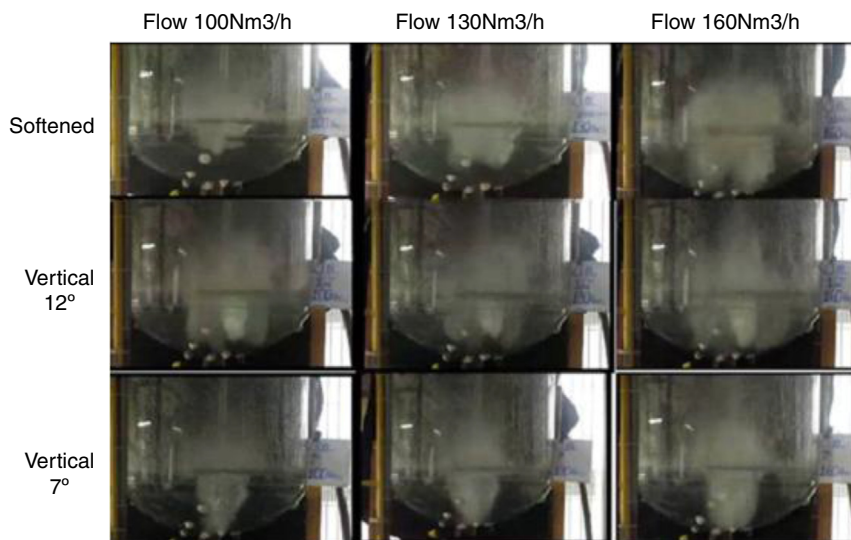


Fig. 14 – Images showing the jet penetration with a 0.180 m height comparing flow effects and tip configuration with an angle to the vertical.

the images of the flow prior to complete turbidity, as shown in Fig. 16.

For tests with the tip 7° with the vertical, the small angle directs the jet to the bottom of the converter, in this case, only when there was a flow reduction (100 Nm³/h) and an increase in the height of the lance (0.250 m) the jet did not reach the bottom of the converter.

In Fig. 17 trials were conducted with tips at 12° to the vertical, the behavior between the calculated and measured values showed good consistency, indicating as expected, that as flow is reduced and height of lance rose, the jet reduces their penetration in the bath. For flow 160 Nm³/h, lance heights of 0.117 and 0.180 m the jet still focused on the converter bottom. Fig. 18 shows the results obtained for 12° vertical softened nozzle.

The calculations for the 12° tip to the vertical and softened nozzle are the same for the tip 12° to the vertical, because for the moment balance the calculation variables are the same. However the measured values differ, usually lower to the vertical 12°. This result is contrary to expectations, according to Maia et al. [13], being attributed to the difficulty of machining operation accuracy due to the reduction of the scale.

From Eq. (5) a graph correlating to the dimensionless penetration was generated, with modified Froude number displayed on as seen in Fig. 19.

The calculation for determining the slope of the straight, the constant K, was done using the free software Eureka Formulize. The K values presented in Table 5 are close to the values found by Maia et al. [13] in experiments using a 1:6 scale converter of industrial reactor.

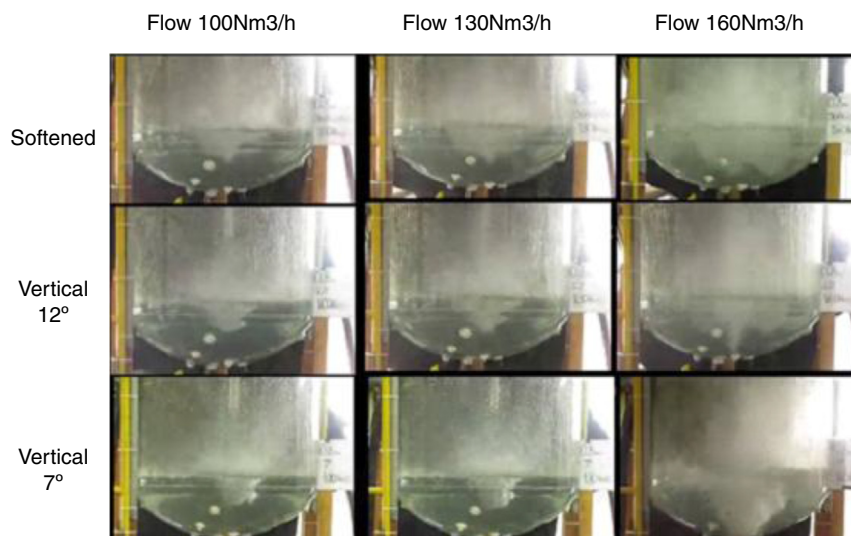


Fig. 15 – Images showing the jet penetration with a 0.250 m height comparing flow effects and tip configuration with an angle to the vertical.

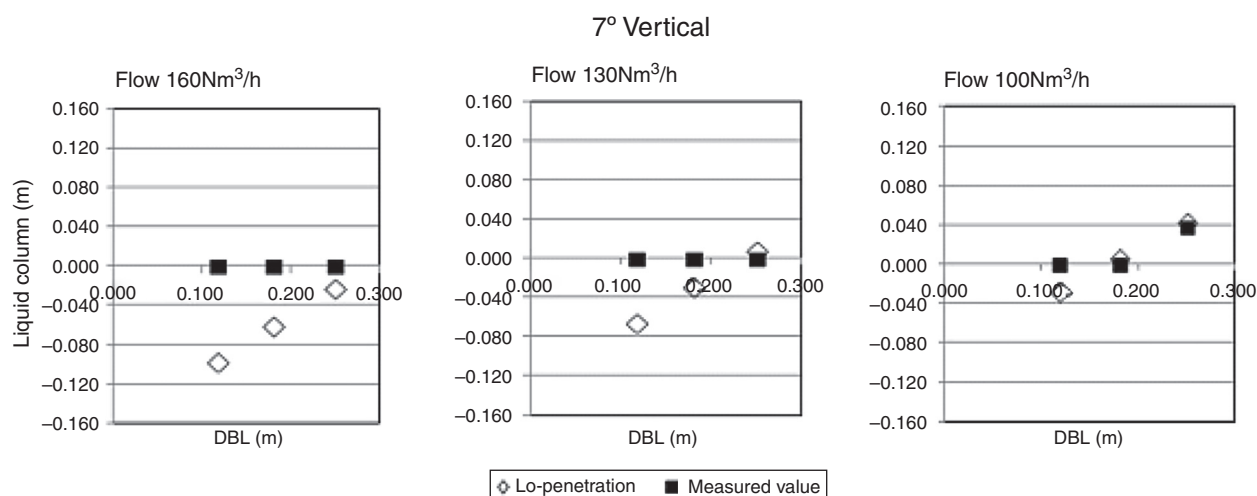


Fig. 16 – Flow × penetration with a 7° tip to the vertical.

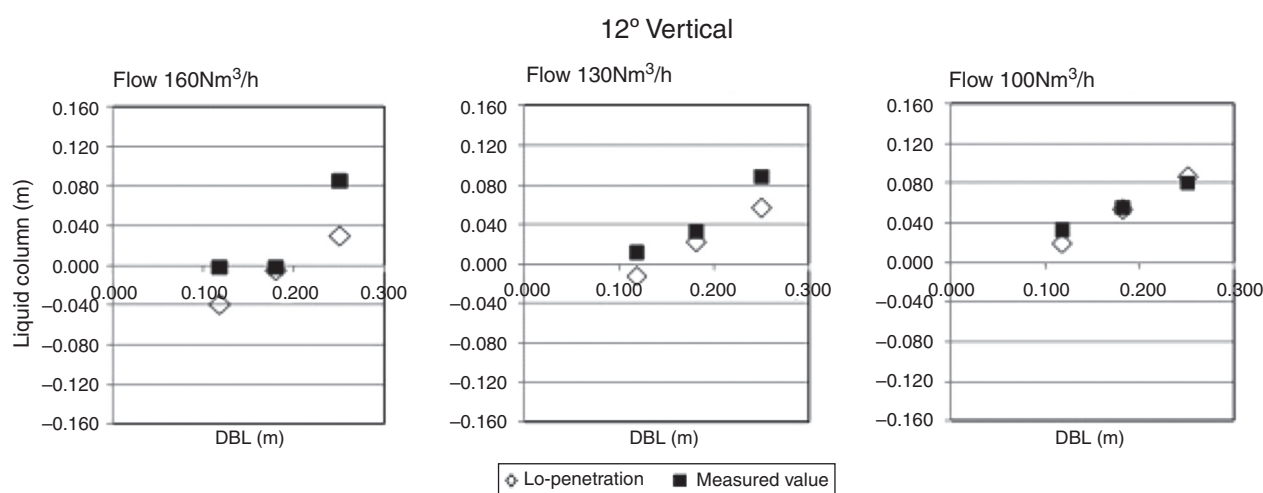


Fig. 17 – Flow × penetration with a 12° tip to the vertical.

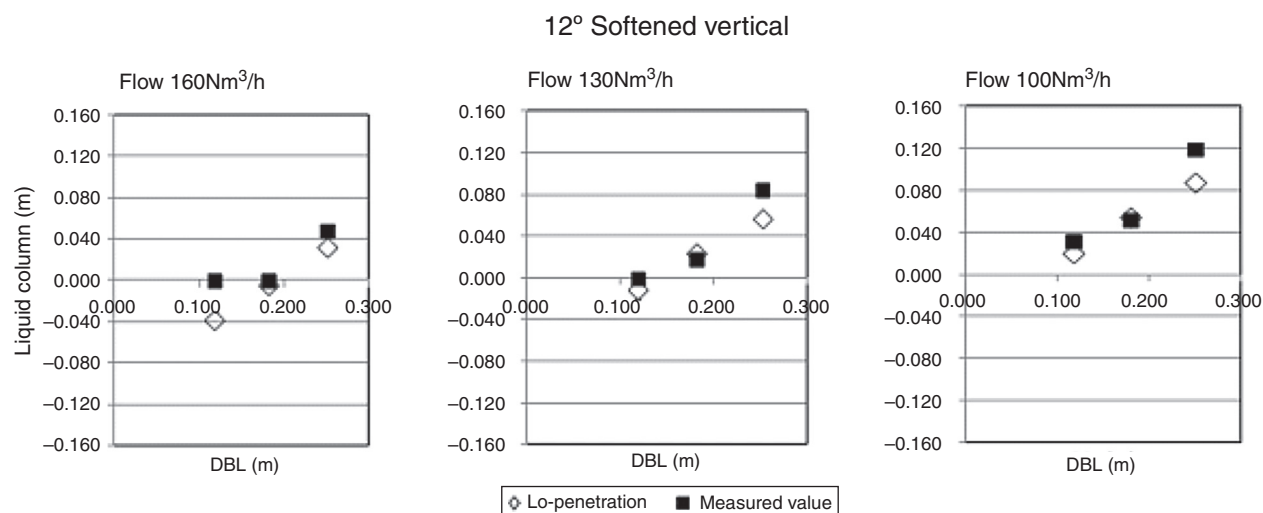


Fig. 18 – Flow × penetration with a softened 12° tip to the vertical.

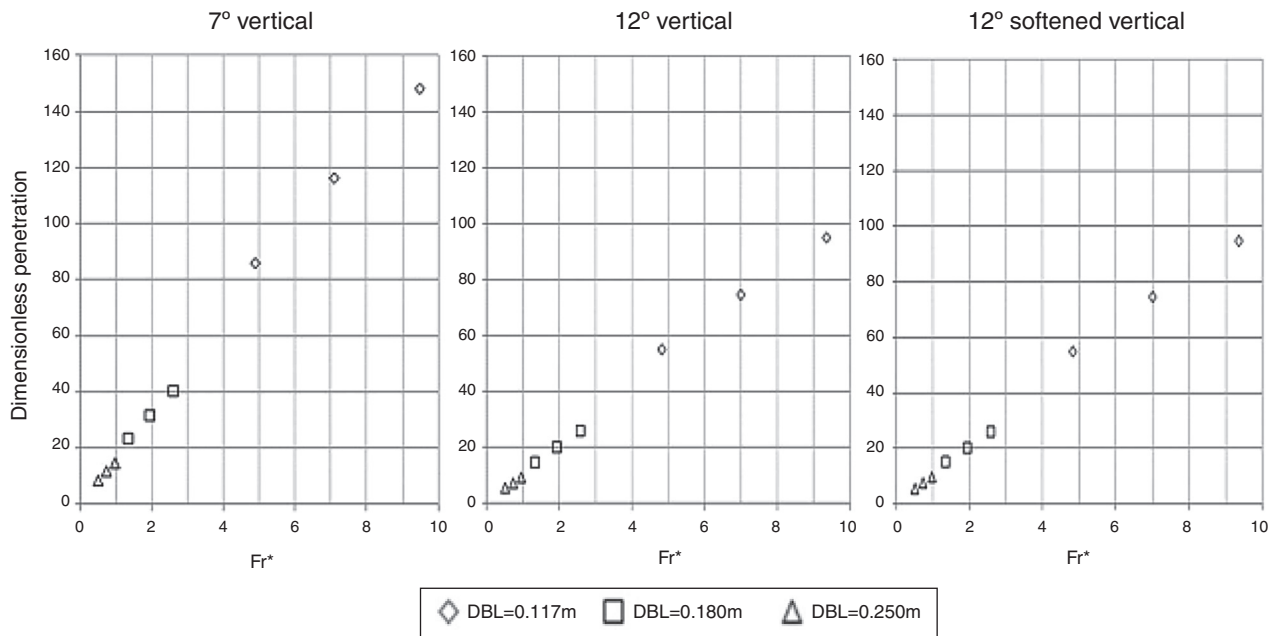


Fig. 19 – Penetration of dimensionless jet $\times$ modified Froude for several lances height, angles to the vertical and softened geometry.

Table 5 – Value of the K constant for different angles to the vertical.

Tip type	K	R^2
7° vertical	5.72	0.99627603
12° vertical	4.63	0.99627582
12° vertical softened	4.62	0.99627582

1. The comparison of jet penetration values showed good consistency ($R^2 > 0.99$).
2. The jet penetration increases with increasing modified Froude number.
3. The values of the constant K between 4.62 and 5.72 found have consistency with other published works.

This work allows continuity in the steelworks correlating changes in the parameters presented and response of the process variables, allowing metallurgical adjustments in refining steel process.

4. Conclusions

The conclusions obtained from the experiments made in the cooling model of Plexiglas in geometrical scale 1/6 for a 220 t BOF vessel converter of steel.

The main conclusions on the jet penetration are:

1. Reducing the distance lance bath (0.118 m) increases the penetration jet and touched converter bottom (0.230 m).
2. The standard tip reaches converter's bottoms at all distances bath lance.
3. The increase of the flow rate ($160 \text{ Nm}^3/\text{h}$) and the distance bath lance (0.250 m) form jet scattering helping gas-water emulsification.
4. The tip with 20° torsion provides independent jets and larger atomization in the bath by jets.
5. The standard tip and 10° of torsion showed coalescence of the jet.

The jet penetration is a good indication of the momentum transfer from the jet to the bath and can be a great tool to guide changes in patterns of lance height, flow and tip configurations in industrial practice.

In this sense the main conclusions are:

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgments

The authors thank Lumar Metals Ltda, for encouraging continued research and support; CNPq, for helping; and Prof. Roberto Parreiras Tavares to Universidade Federal de Minas Gerais (UFMG) for LASIP structure (Laboratory for Process Simulations). They also thank FAPEMIG for the financial project: PPM-00118-13, Title: MODELAGENS FÍSICA E MATEMÁTICA DO ESCOAMENTO MULTIFÁSICO EM REATORES METALÚRGICOS and to Mr. Shrinivas Raju for English corrections.

REFERENCES

- [1] Glass DR, Smith GC. Nozzle theory. In: BOF steelmaking. Vol. III: Design. New York: The Iron and Steel Society of the

- American Institute of Mining, Metallurgical and Petroleum Engineers, Inc.; 1976 [chapter 8].
- [2] Glass DR, Smith GC. Nozzle theory, vol. I. New York: BOF Steelmaking; 1974.
- [3] Odenthal HJ, Emling WH, Kempken J, Schluter J. Advantageous numerical simulation of the converter blowing process. AISTECH; 2007.
- [4] Meidani ARN, Isac M, Richardson A, Cameron A, Guthrie RIL. Modeling shrouded supersonic jets in metallurgical reactor vessels. ISIJ Int 2004;44:1639–45.
- [5] Diaz-Cruz M, Morales RD, Olivares O, Elias A. Physical and mathematical models of gas–liquid dynamics in BOF converters. In: Steelmaking conference proceedings. 2002. p. 737–48.
- [6] Diaz-Cruz M, Iida T, Komarov SV, Sano M. Mixing characteristics under gas injection through rotary lance submerged in liquid bath. ISIJ Int 1995;35:464.
- [7] Naito KI, Ogawa Y, Inomoto T, Kitamura S, Yano M. Characteristics of jets from top-blown lance in converter. ISIJ Int 2000;40:23–30.
- [8] Mundim MJ. Tecnologia de Fabricação do Aço Líquido, vol. 2, 3ª ed. Belo Horizonte: ACIARIA LD, UFMG; 1985.
- [9] Szekely J, Themelis NJ. Rate phenomena in process metallurgy. 1st ed. Montreal: John Wiley & Sons; 1971, 784p.
- [10] Carneiro FL. Análise Dimensional e Teoria da Semelhança e dos Modelos Físicos. Rio de Janeiro: Editora UFRJ; 1996 [1ª Edição 1993].
- [11] Maia BT, Martins AAR. Lança de Oxigênio. In: Curso de Aciaria à Oxigênio. Rio de Janeiro, RJ: Associação Brasileira de Metalurgia e Materiais – ABM; 2012 [chapter 8].
- [12] Higuchi Y, Tago Y. Effect of nozzle twisted lance on jet behavior and spitting rate in top blown process. ISIJ Int 2003;43:1410.
- [13] Maia BT, Alvarenga JA, Reis RF, Tavares RP. Effects of the use of twisted nozzles on jet-bath interaction and on mixing time in a BOF top blow converter. In: 6th European oxygen steelmaking conference. 2011. p. 1–12.
- [14] Maia BT, Barros JEM, Nascimento LM, Guerra MSL, Tavares RP. Simulação Numérica do Soplo de Oxigênio através de Bocal Supersônico. Rev Tecnol Metal Mater Miner 2012;9.
- [15] Staschower M, Moreira JRS [Iniciação Científica da Escola Politécnica de São Paulo] Estudo Experimental de Escoamento de Gases em Bocais Convergente Divergente. São Paulo: Departamento de Engenharia Mecânica da EPUSP; 2002.
- [16] Shapiro HN, Moram MJ. Fundamentals of engineering thermodynamics. New York: John Wiley & Sons; 1988. p. 417–35.
- [17] Deo B, Assis PS. Process dynamics of oxygen steelmaking. ABM – Course, Indian Institute of Technology – Kanpur, Escola de Minas: UFOP; 2006, 328p.
- [18] Alam M, Irons G, Brooks G, Fontana A, Naser J. Inclined jetting and splashing in electric arc furnace steelmaking. ISIJ Int 2011;51:1439–47.
- [19] Alam M, Naser J, Brooks G, Fontana A. Computational fluid dynamics modeling of supersonic coherent jets for electric arc furnace steelmaking process. Metall Mater Trans B 2010;41B:1354–67.
- [20] Alam M, Naser J, Brooks G, Fontana A. Computational fluid dynamics simulation of supersonic oxygen jet behavior at steelmaking temperature. Metall Mater Trans B 2010;41B:636–45.
- [21] Smith GC. Multiple jet oxygen lances. Theoretical analysis and correlation with practice. J Met 1966:846–51.