ABSTRACT
The practice of slag splashing is already consolidated industrially. However, there are still uncertainties about the relationship of the lance parameters and their effects on the slag. This article presents a comparison of the similarity of two 300t converters, one in Ukraine and the other in Brazil, with the 1/10 scale acrylic model of the LASIP located at the Federal University of Minas Gerais and their respective slag splashing patterns. The results will be compared using an improved version of the equation of motion in determining the jet penetration over the slag layer and the ejection of material to cover the refractory walls.

Keywords: BOF, Slag Splashing, Bottom Burn, Equation, Cold Model, Industry set-up.

INTRODUCTION
Splashing slag is today the most modern preventive repair technique of refractory material. Despite the high value of the initial investment for implementing the system for the execution of this practice, most BOF plants opted for its installation due to the rapid return on this investment. The slag splashing technique consists of blowing inert gas at high flows to project the slag on to the walls of the refractory coating\(^{(11-15)}\).

Currently, the projection techniques practice adopted for the projection of slag on the wall of the converter consists of the following steps:
- Descent from the lance to the maximum mechanical stop;
- Maximum opening of the nitrogen valve;
- Projection of material to the wall of the converter with static lance.

However, this adopted practice may not reflect the best material projection condition on the converter wall, because as the lance is held static, the projection of slag directly hits a point and from this point flows through the walls of the converter, as shown in Figure 1.
Figure 1. Projection technique currently adopted (1-3).

For probe distances (DBL) closer to the bath, the jet thrust is high enough to reach the bottom of the converter. In the hypothetical case, when there is no physical limitation imposed by refractory bricks, penetration would reach higher than the slag layer. However, based on the calculations in which penetration reached the refractory, a new theory is proposed: it is assumed that the resistance imposed on the jet when it touches the refractory in combination with the force of penetration leads to the generation of a new factor that can contribute to the displacement of the slag to the refractory wall.

This new factor is attributed to a supposed penetration cylinder, whose construction is carried out assuming that the jet pierces the sole. As this phenomenon cannot occur, the cylindrical shape of the jet is considered as the basis. Through this cylinder, the volume is determined and can be converted to mass, which, in turn, will be associated to an increase of turbulence in the slag. Thus, the mass displacement to the side walls of the furnace is favored and, as a consequence, the slag covers refractory walls of the converters instead of the projection to the converter mouth region or region of the trunnions. As this is a proposed theory, it will be studied in order to correlate the analytical calculations with practical results from physical cold simulation. Figure 2 represents the proposed theory.

Figure 2. Penetration cylinder formation theory for very high jet moment quantity (1-3).

Simultaneously with the adopted practice, a new form was suggested to execute the activity, which consists of steps similar to the practice described previously. But, projection of material for the wall of the converter with lance in movement, doing "yo-yo" effect.

Keeping the lance moving during slag splashing, the slag projection on converter wall is not restricted to a single point, but to several other points, as shown in Figure 3.
The points to be hit will vary according to lance heights defined. It is worth mentioning that the existing converters are of different type and shape; therefore, for each type of converter, an isolated study for the proper lance positions is required.

**METHODOLOGY**

For the preparation of this article, the following steps were performed:

1. Determination of industrial plants;
2. Survey of industrial parameters for slag splashing execution;
3. Similarity study considering the maximum pressure and flow limit of the compressor of the process simulation laboratory of UFMG - LASIP;
4. Determination and execution of the test matrix
5. Adequacy of the moment balance equation developed by Willian\(^{(16)}\) for the slag splashing parameters
6. Determination of factor K from the penetration results of trials;
7. SplashIndex Determination.

Table 1 below shows the industrial data of two 300t converters and LASIP conditions\(^{(1,4)}\).
A large volume of studies is conducted to obtain steel/water similarity. In this study, Froude number is one of the main similarity criteria after the number of Mach. Table 2 presents the test array that trials.

### Table 2. Test Matrix for Two Slag Layer Conditions

<table>
<thead>
<tr>
<th>Molten slag depth</th>
<th>Number and angle nozzles</th>
<th>Air Flow</th>
<th>Heigh lance from molten slag (m) DSL</th>
<th>Molten slag depth (m)</th>
<th>Number and angle nozzles</th>
<th>Air Flow (m3/h)</th>
<th>Heigh lance from molten slag (m) DSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,03</td>
<td>5# 14°</td>
<td>130</td>
<td>0,35</td>
<td>5# 14°</td>
<td>130</td>
<td>0,32</td>
<td>0,42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>160</td>
<td>0,35</td>
<td>160</td>
<td>0,32</td>
<td>0,42</td>
<td>0,62</td>
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<td></td>
<td></td>
<td>0,85</td>
<td>0,85</td>
<td>0,82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,06</td>
<td>6# 17,5°</td>
<td>130</td>
<td>0,35</td>
<td>6# 17,5°</td>
<td>130</td>
<td>0,32</td>
<td>0,42</td>
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<tr>
<td>0,03</td>
<td>Rotox 5#</td>
<td>130</td>
<td>0,35</td>
<td>Rotox 5#</td>
<td>130</td>
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<td>0,85</td>
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<td>0,82</td>
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</tr>
</tbody>
</table>

In Table 2 with the change of the slag layer and predetermined positions of the lance height in relation to the top, the distance of the slag layer lance was made.

For this study, it was necessary to adjust the dimensionless number because the element used to represent the slag were 3mm polystyrene spheres. To determine jet penetration, the moment balance equation was used according to Equation 1 in its recent review presented by Willian(16).
\[
\frac{\pi}{2K^2} \cdot \frac{P}{DBL} \cdot \left(1 + \frac{P}{DBL}\right)^2 \cdot \left[1 + \left(\frac{P}{DBL}\right)^{-2} \cdot \frac{\cos \theta \cdot (\sigma_{steel} + \sigma_{slag})}{(\rho_{steel} + \rho_{slag}) \cdot g \cdot DBL^2}\right] = \frac{\pi}{4} \cdot \frac{\rho_{gas} \cdot (V_{exit} \cdot D_{exit} \cdot \cos \theta)^2 \cdot n}{(\rho_{steel} + \rho_{slag}) \cdot g \cdot DBL^3} \quad (1)
\]

After some simple algebraic manipulations, Equations 2 to 4, Equation 5 can be rewritten:

\[
P^* = \frac{P}{DBL}
\]

\[
Eo^* = \frac{(\rho_{steel} + \rho_{slag}) \cdot g \cdot DBL^2}{\cos \theta \cdot (\sigma_{steel} + \sigma_{slag})}
\]

\[
Fr^* = \frac{\pi}{4} \cdot \frac{\rho_{gas} \cdot (V_{exit} \cdot D_{exit} \cdot \cos \theta)^2 \cdot n}{(\rho_{steel} + \rho_{slag}) \cdot g \cdot DBL^3}
\]

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

where: \(\rho_{gas}\) - density of the gas at the nozzle outlet (kg.m\(^{-3}\)), \(g\) the acceleration of gravity (m/s\(^2\)), \(\rho_{steel}\) - density of liquid steel (kg.m\(^{-3}\)), \(P\) - penetration jet (m), \(\sigma_{steel}\) - 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, \(\theta\) - angle of inclination of the nozzle, \(\sigma_{slag}\) - surface tension of the slag (N.m\(^{-1}\)), \(\sigma_{steel}\) - surface tension of steel (N.m\(^{-1}\)), \(\rho_{mix}\) - density of the mixture of steel, slag and gas (kg.m\(^{-3}\)), \(n\) - number of nozzles, \(P^*\) - dimensionless penetration of the jet, \(Eo^*\) - modified number Eötvös and \(Fr^*\) - modified Froude number.

In addition to the traditional nozzles presented in Table 1, tests with concept nozzle were performed with torsion parameters between the nozzles that in this experiment causes a rotation of the nozzle.

The lance tips used in the experiments have the same slope with respect to vertical and output diameter. The difference between the nozzles is in the angle generated by the convergent input position and the divergent output position of the gas. In Figure 4, top and side views show the difference between nozzles.

![Figure 4. Comparison between (a) normal nozzle and (b) torsion nozzle.](image)

In Figure 4, the lance with a 0\(^{\circ}\) rotation angle corresponds to the normal nozzle (a). The nozzle with a twisting angle is defined in (b). The lance axis originates from point “P”, the nozzle input is at point “I” and the output at point “O”. Point “B” is the
intersection of the nozzle shaft and the bath surface. The torsion angle is defined as the angle between the PO and PI lines (8-10).

Two slag masses were also considered common. The first being a typical amount of end of blow and the second with higher mass considering additions of heaters.

In the present work, it was considered a 100% liquid slag, the effects of viscosity or solidification of the slag was not considered. The tests were filmed from lateral and top position in order to evaluate the penetration and projection of the jet over the slag and its spreading on the walls of the converter, range and effects on the blow lance.

Factor K was estimated because it was not possible to accurately measure, since in the vast majority of tests the jet touched the bottom of the converter. And when not, there was no favorable condition for this determination.

SplashIndex(7) values the conjugated effect between penetration and area projection. This index is a difference in the percentage shape of these two parameters and is therefore dimensional. Index calculated from the difference between percentage penetration and projected percentage area, as Equation 6 and Figure 5 below:

\[
\text{SlagSplashIndex} = \frac{L}{L_0} - \frac{D_{cav}}{D_{bottom}}
\]  

(6)

where: L - jet penetration (m), L_0 - static bath height (m), D_{cav} - diameter of the jet projection on the liquid or solid slag layer (m), D_{bottom} - diameter of the converter sole (m).

Figure 5. Lance height against jet impingement behavior into slag during slag splashing(7).

The first term of the equation is obtained from a moment balance and the second term from that of trigonometric relationships. Positive values indicate a predominium of the effects of jet penetration while negative values indicate a predominance of the effects of the jet range on the projected area on the bath surface.

Green Line - Represents Splash Index - a relationship between the penetration of the jet into the slag x the opening of the cavity on the surface of the slag. As the lance advances toward slag, the area projects over its surface reduces and jet penetration increases.

Yellow Board - Represents penetration greater than 100%, that is, the jets exceed the slag layer reaching the converter refractory. In the calculations were not imposed the restriction created by the refractory, because this quantification will be used to estimate the mass of slag that the jet is able to move from the base of the converter to the region of the cylinder, “pushing” the slag through the walls, without being by spreading. For the spread, the amount of slag assumed, will be that referring to the volume that the nitrogen jet covers and displaced during its passage through the slag layer.
Blue board - Represents the area with negative values calculated by the Slag Splashing Index equation (%). This region represents the projection area of the jet, which in general has a large projection diameter and small or no jet penetration. The more negative, the more likely the jet will not penetrate the slag layer.

Orange board - “Burn Bottom” - Represents the recommended area for sole blowing with the “Burn-Bottom” technique. In this case, the slag layer is solidified at the bottom of the converter. Thus, with the intention of not spreading the material in the upper regions of the converter, but a dissipation of energy over the solidified layer. The jet focusing and dissipating on the solidified layer will potentially oxidize some remaining steel and this dissolve the layers, generating cavities in the direction of the jets. So the 200% reference means a small or insignificant projection of area but a strong jet penetration. Splash index arbitrated 80 and 180.

Red Board - “Yo-yo” - Represents the recommended area for slag splashing with the technique “Yo-Yo”. In this case, considering a layer of liquid slag with slag spreading. The performance limit of the splash is the slag layer itself. Splash index arbitrated 20 and 160.

**DISCUSSION**

Figures 6 to 8 shows images from the tests in Table 2 for 0.030m slag layer. The images were grouped by nozzle type and distinct by the flow rates.
Figure 6. Jet penetration for lance tip 05 nozzles, slag layer 0.030m and various lance heights being: a) flow 130Nm³/h and b) flow 160Nm³/h.
Figure 7. Jet penetration for lance tip 06 nozzles, slag layer 0.030m and various lance heights being: a) flow 130Nm³/h and b) flow 160Nm³/h.
Figure 8. Jet penetration for lance tip 05 nozzles with 10° torsion, slag layer 0.030m and various lance heights being: a) flow 130Nm³/h and b) flow 160Nm³/h.

Figures 9 to 11 shows images from the tests in Table 2 for 0.060m slag layer. The images were grouped by nozzle type and distinct by the flow rates.
Figure 9. Jet penetration for lance tip 05 nozzles, slag layer 0.060m and various lance heights being: a) flow 130Nm$^3$/h and b) flow 160Nm$^3$/h.
Figure 10. Jet penetration for lance tip 06 nozzles, slag layer 0.060m and various lance heights being: a) flow 130Nm$^3$/h and b) flow 160Nm$^3$/h.
Figure 11. Jet penetration for lance tip 05 nozzles with 10° torsion, slag layer 0.060m and various lance heights being: a) flow 130Nm³/h and b) flow 160Nm³/h.

From the images of Figures 6 to 11, the jet penetration was estimated in the experiments to which the jet did not touch the bottom of the converter and then determined the K factor and calculated the penetration according to Equation 1. The results are presented in Figures 12 and 13, in pairs in order to allow better comparison with effect of the slag layer.

It is possible to observe the influence of the amount of slag on the behavior of its movement. Smaller amounts are lower jet resistance and their penetration.

In cases of low lance height and associated with low flow it is sometimes possible to notice that the dissipated jet on the bottom of the vessel has enough strength to sustain all suspended slag mass. This behavior is no longer observed when the slag mass doubles in quantity. In the condition of higher slag volume, the jet penetrates the layer and also dissipates over bottom, but causing a revolving of the mass in the lower layers with limit region near half of the lower cone.

Figure 12. Jet penetration calculated for lance tip 05 nozzles, two flows and various lance heights being: a) slag layer 0.030m and b) slag layer 0.060m.
Figure 13. Jet penetration calculated for lance tip 06 nozzles, two flows and various lance heights being: a) slag layer 0.030m and b) slag layer 0.060m.

The results with torsion nozzle were similar to their respective nozzle 05 nozzles. The similarity is due to the fact that the exit and throat dimensions are the same as the vertical angle. The inserted torsion angle did not cause any change in the angle with the vertical, so the projection of the jet on the surface of the slag layer was maintained.

However, the effect of the new angular component and the new direction imposed on the particles ejected from the bath is remarkable in the images. The result of this targeting was a shorter range of polystyrene. In industrial practice a condition not favorable to slag splashing, but with potential for blowing, as it reduces the height of reach of particles reducing the probability of skull lance formation and upper cone of the converter, containing the level of the emulsion at lower heights.

The figures are compared to the penetration calculated by the moment balance with 02 flows and 04 lance heights for 03 different types of nozzles. It is noted that with increased flow and reduction of the lance height, the penetration grows and the area projected on the bath (in the case by way of comparison the reference used was the diameter of the bottom) reduces.

It is important to comment on which projection value was obtained by trigonometry considering the angle with the vertical added to the semiangle of nozzle output and lance height.

In the experiments it is observed that only in some heats with higher slag volume, double, the jet does not reach the bottom. But it is evident that the ejection of particles is higher the higher the lance height. So in operational practices, high lances are conducive to the coverage of the upper cones of the converters.

The behavior of penetration and its consequences on slag is worth in-depth discussion because added to the extension of the jet designed to propose different mechanisms from the normal ones generating, perhaps, a new paradigm:

- angles influences the ejection direction of the particles;
- lance height determines the range of this ejection;
- low height - may indicate a dissipation of the jet force on the bottom (can be good resources to evaluate the blow to reduce the bottom build up);
- high heights and consequent increase of area determine the scattering of the ejection directions;
- flow alternation or nozzle pressure, imposes the agitation of the system and the displacement of the mass because in the nozzle with rotation a profile is formed in the stable bath with less ejection of particles (unwanted practice for slag splashing but very timely for the primary refining of the steels)

Now, considering and comparing the films, a K factor for polystyrene has been estimated. This is due to the fact that it is not easy to determine the penetration of the jet and almost always the jets touch the bottom. In some cases that did not touch, it was possible to estimate the level of penetration.

With the lance tip with torsion due to the same vertical angle, the penetration of the jet and the projection over the slag layer are the same as 05 nozzles. That calculations are the same, but the behavior aspects are very different.

Thus, it generates demand to develop a mathematical model that represents this new component of directions on the slag layer.
Comparing the behavior of the Slag Splashing Index it is possible to observe that the areas of covers to perform the bottom blowing and refractory protection as it is influenced by the blow flow and angle with the vertical.

High flows are offset by higher lance for the same Slag Splashing Index. With respect to the angle with the vertical, the greater the angle closer to the bath the lance should be.
CONCLUSION

The main conclusions of this work are:

- The slag layer determines the behavior of slag splashing;
- Thin layers of slag, jet can dissipate on the bottom of the converter; In general, the higher the flow rate and lance height, the greater the splashing capacity of the jet;
- The torsion nozzle introduces a new component by changing the overall behavior of ejected particles to lower ranges when compared to traditional nozzles;
- The K factor of Equation 1 was estimated because in a few tests it was possible to evaluate jet penetration;
- Even with an estimated K-factor value, Equation 1 is useful in industrial practice to predict slag splashing behavior;
- Slag splashing Index was able to reflect these situations;
- For the torsional nozzle, it is necessary to develop an equation to reflect its effects, because Equation 1 does not describe the effect of this angular component on the bath.

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REFERENCES


