Practical Approach of Penetration Index Equations for Use in BOF Blowing Pattern Design

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ABSTRACT

Several equations are developed over the years to calculate the penetration depth L of the Oxygen jet generated by the blowing lance for BOF/LD converters and similar processes. The penetration depth L for a given lance tip is primarily impacted by the lance height (gap), the oxygen flow rate and the resulting Oxygen jet momentum. Considering a dimensionless parameter L/Lo, where Lo is the liquid steel bath height, this paper will critically review both the theoretical and practical aspects of these depth of penetration equations, and recommend the most feasible equation(s) to determine the lance gap to use during the oxygen blow. Further the effects of the penetration depth, like: total surface of the penetration cavity, which is the reaction surface for direct reaction of Oxygen with the metal bath, and droplet generation and size, which is the reaction surface for reaction of Fe droplets with slag FeO will be discussed.

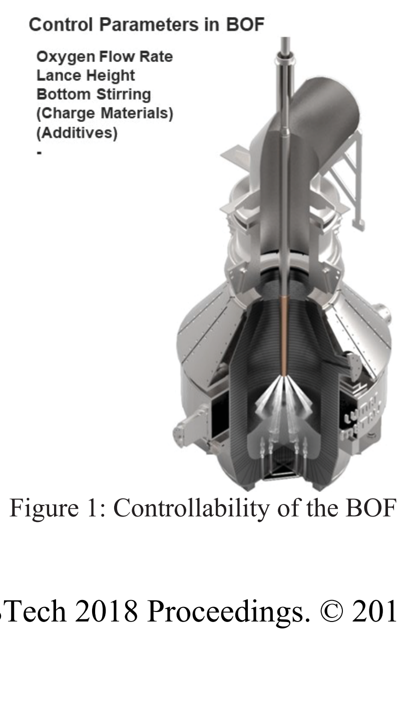


Figure 1: Controllability of the BOF Process

INTRODUCTION

The Basic Oxygen Process (BOP) is a long time operated process for steelmaking by use of hot metal, scrap and flux and refining by Oxygen gas. Numerous papers about the process fundamentals and reactions going on during the blow have been published. Numerous lab scale, half industrial and industrial trials have been carried out to understand the behavior of the process. All operators of BOF furnaces know, that still the process is not monitored and controlled completely and undesired reactions and effects occur on regular basis. The main problem is as opposed to fully controlled processes the controllability of the BOF operation is limited by the fact that it is impossible to look inside the furnace and directly react to process changes, Figure 1.

Unfortunately for the process control in the BOF only a few tools can be used and the feedback of the tools always is an indirect indication. The main blowing tool is the blowing lance which feeds the Oxygen gas to the metal bath surface. The Oxygen flow rate and the lance height can be changed, other design parameters like the number of nozzles and the nozzle dimensions are fixed for a given furnace. Other tools are bottom stirring and the type and amount of flux and coolants added into the furnace by bulk charging systems. The on-line control instruments are, if installed, off-gas analysis, sublance temperature measurement and vibration or audio control devices. The process result is checked after the process by metal and slag composition analysis. It is common procedure to operate BOF furnaces by application of charge recipes and blowing patterns.

BOF BLOWING PATTERNS

The BOF blowing patterns in general can be split into the different stages of the process happening one after the other or simultaneously, as described in Figure 2.

BOF blowing patterns can be in general divided into 7-9 phases in which the lance height and (maybe) the Oxygen flow rate must be adjusted to the required metallurgical steps. The phases to be recognized are:

Phase 0: Opening of the Oxygen flow valve: At start of the blow the Oxygen valve is opened in 2-3 intermediate steps (70%, 90%, 100%) to avoid overshooting of the controller.

Phase I: Ignition: the selected starting lance height must be sufficient to guarantee bath penetration depth for immediate ignition on the one hand. On the other hand damage of the lance tip caused by protruding scrap must be avoided.

Phase II: Slag formation (FeO): in the beginning of the blow the lance is operated at a high level and with full Oxygen flow to achieve sufficient FeO generation required for quick lime solution. The total amount of the lime charge depends on the Silicon content of the hot metal (Si_{HM}). Due to this fact the length of this period also depends on the Si_{HM}. Early and quick slag formation is a key factor to reduce lance skull formation.

Phase III: Slag formation (SiO_2): It is recommended to reduce the lance height at the end of the Si_{HM} oxidation to keep the oxidation speed at a high level.

Phase IV: De-Phosphorization (P_2O_5): At the point of decreasing Si_{HM} oxidation speed, De-Phosphorization at low metal/slag temperature starts. The speed of the Phosphorus oxidation can be increased by reduction of the lance height. The length of this phase is between 500-800 m_n^3 Oxygen depending on the size of the BOF vessel.

Phase V: De-Carburization (high speed dC/dt): The start of this phase is characterized by a maximum in the CO_2-curve and the strong incline of the CO-curve in the off-gas. In this phase the critical path is to drive the lance quickly down to a position where the CO-content of the gas reaches to a level valuable for recovery (rich gas).

Phase VI: De-Carburization (medium speed dC/dt): The lance height must be adapted to the declining De-C speed.

Phase VII: De-Carburization (low speed dC/dt): The lance height must be further decreased to hold the CO-content in the off-gas as long as possible in the limits for gas recovery.

Phase VIII: Dynamic end-point control (after sublance measurement): At the decline of the De-Carburization in many BOF-shops a sublance measurement for temperature and sampling is carried out. Based on his measurement the heat is conditioned with cooling agent and Oxygen or dynamic endpoint. During the sublance measurement it is recommended to reduce the Oxygen flow (65% of the aim flow rate) to reduce the turbulences in the BOF. After the measurement the Oxygen flow is set back to the aim. In case of dry slag it might be advantageous to increase the lance height slightly to increase the FeO content of the slag and to enhance De-Phosphorization at the end of the blow.

The bottom stirring flow rate is adjusted from the beginning (until the middle of the blow) at minimum flow to keep the plugs clear. At 75% of the blow medium flow rates are adjusted. After the sublance measurement the bottom gas rate is turned to maximum flow to promote bath mixing forces. The time for the so called "post stirring" shall be adjusted to a minimum of 90 sec.

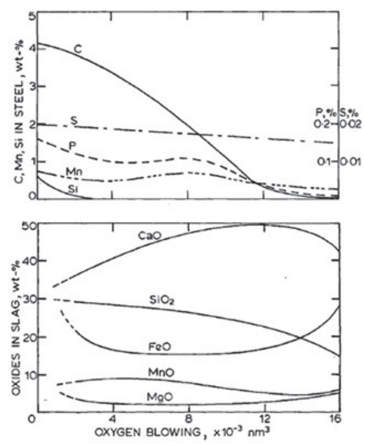


Figure 2: General rules for BOF blowing patterns and composition of metal and slag during the blow

Starting from ignition the slag formation by oxidation of [%Fe], [%Si] + [%Mn], and [%P] is the first important phase of the process. In this phase only little De-Carburization is observed. In the middle of the blow, as soon as the other hot metal components have been oxidized to slag, the main De-Carburization starts in the initial stage with high speed, later at decreasing contents in the bath with lower speed. In the high speed phase the consumption of Oxygen for De-Carburization is higher than offered by the blow so a reduction of the slag (%FeO) occurs which is accompanied with a simultaneous reduction of (%MnO) and (%P_2O_5) as well. This so called Mn- and P-reversion has been proven in many trials with in-blow sampling from various researchers. The De-Carburization rate can be maintained by increasing the jet force until towards the end of the blow where the rate suddenly collapses. At this point end point control models based on off-gas analysis or sublance/drop-sensor measurements are started to finish the blow at the desired Carbon and Phosphorous content and temperature in the melt and the desired oxygen activity (%FeO) in the slag. The slag and metal composition are of course linked together. From this theoretical approach it must be estimated that blowing patterns applied in the BOF shops around the globe are following these general rules and the basic understanding of the process model.

In Figure 3 actual blowing patterns applied in different plants are compared schematically. The converter tap weight size in this comparison ranges from 65-320 t, the lance tip design from 3-6 holes with angles of 14-23° and the final lance position ranges from 150–220 cm. Some plants operate with constant Oxygen flow, others with progressive Oxygen flow, and in some plants the flow is significantly decreased in the first half of the blow. The first 4 graphs in Figure 3 show plants without bottom stirring. The lower five graphs of the figure, plants with application of bottom stirring are shown. It becomes obvious that vigorous bottom stirring is applied in the second half of the blow and towards the blow end.

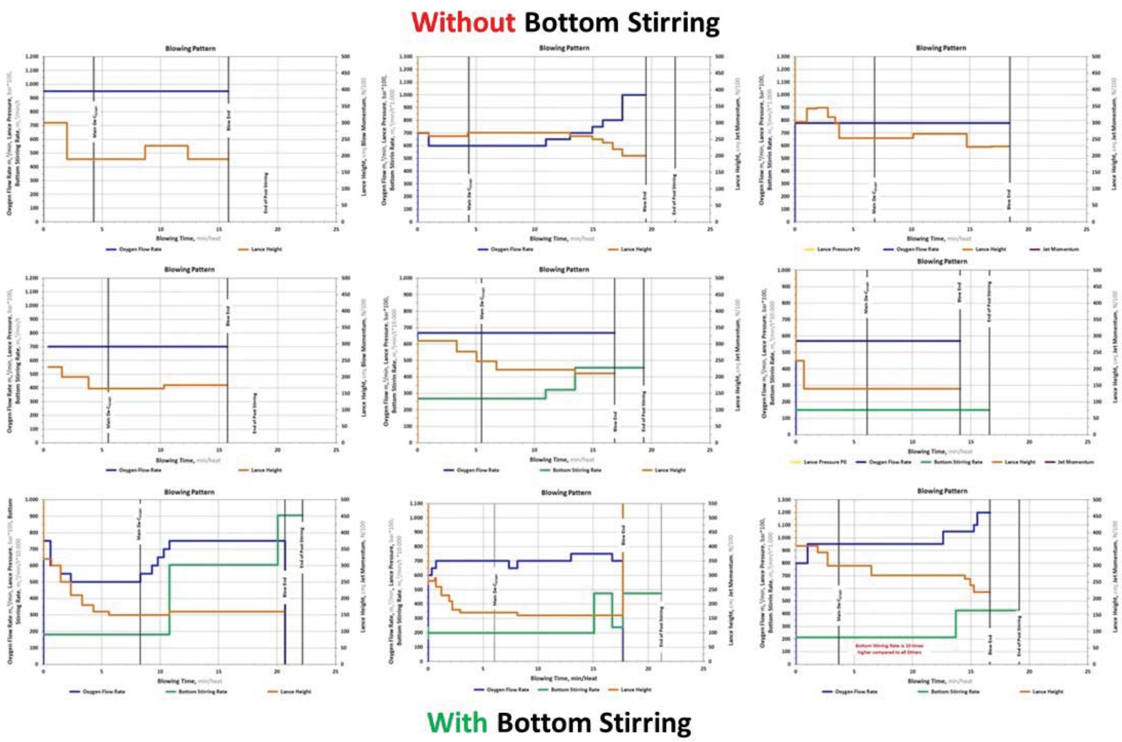


Figure 3: Comparison of various Blow Profiles from different Plants

Although in the Figure 3 only a few examples could be selected and shown, it can be estimated that the variety of blowing strategies will further increase when following the general rules postulated before. It is obvious, that although the BOF process is a deeply investigated phenomena with numerous researchers having investigated and published their results from lab, semi industrial and industrial trials, the daily operation practice in the BOF-shops is an empirical approach. It is rather based on control of undesired effects like lance and mouth skulling, slopping, visible emissions and other, than on model based design of measurable parameters.

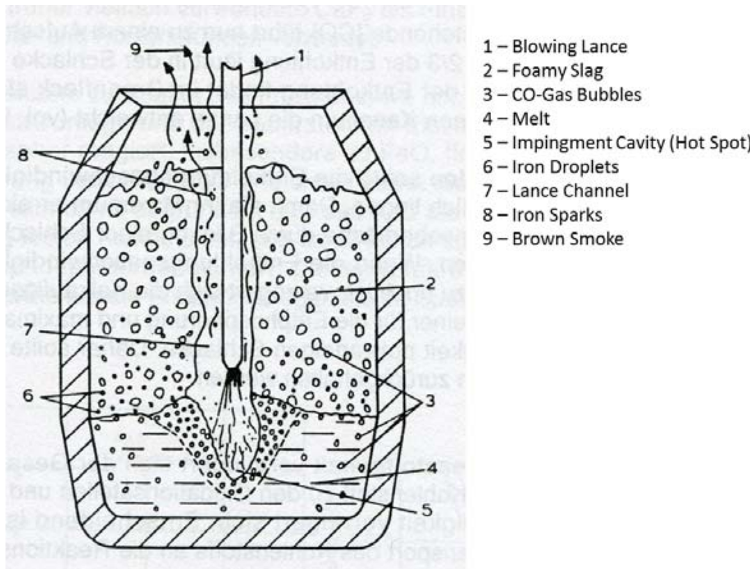


Figure 4: Interface model concept during blowing of a BOF vessel

MODELLING THE BOF PROCESS

The general understanding of the BOF process is shown in the next Figure 4. The Oxygen jet dispatched from the multihole lance tip creates a cavity on the bath surface surrounded by a wave ridge. In this slag free cavity the Oxygen jet reacts directly with the liquid metal inside the vessel. This area can be defined as the Jet/bulk metal interface. The secondary effect induced by the jet is droplet generation and ejection towards the walls. Above the bulk metal and between the wave ridge and the walls there is some bulk slag in this area a bulk slag/bulk metal interface is located. Most of the slag will be foamed to a emulsion generated by CO-gas bubbles formed inside the bulk metal by oxidized metal droplets sinking back into the bath or by metal droplets being oxidizes in the high (%FeO) containing slag foam. Around the lance there is a channel to release gas generated from the jet impact reaction to the mouth of the converter. This channel also is the main source for dust and iron sparks leaving the vessel into the off gas collecting system. The dominant role of the lance position and flow control is obvious.

In this model the operation of a bottom stirring system (low rates of 0,03-0,09 m_n^3/min/t) does not play any role in the initial stage of the blowing process. The low flow bottom stirring is valuable in supporting bath mixing towards the end of the blow when the lance is already in the low position and the De-Carburization rate is declining. And it helps after the sublance measurement and during the post stirring that equilibrium is achieved between bulk slag and bulk metal. The effect of higher bottom stirring rates (0,20-0,50 m_n^3/min/t) or bottom blowing rates by using Oxygen is not included into the recent work.

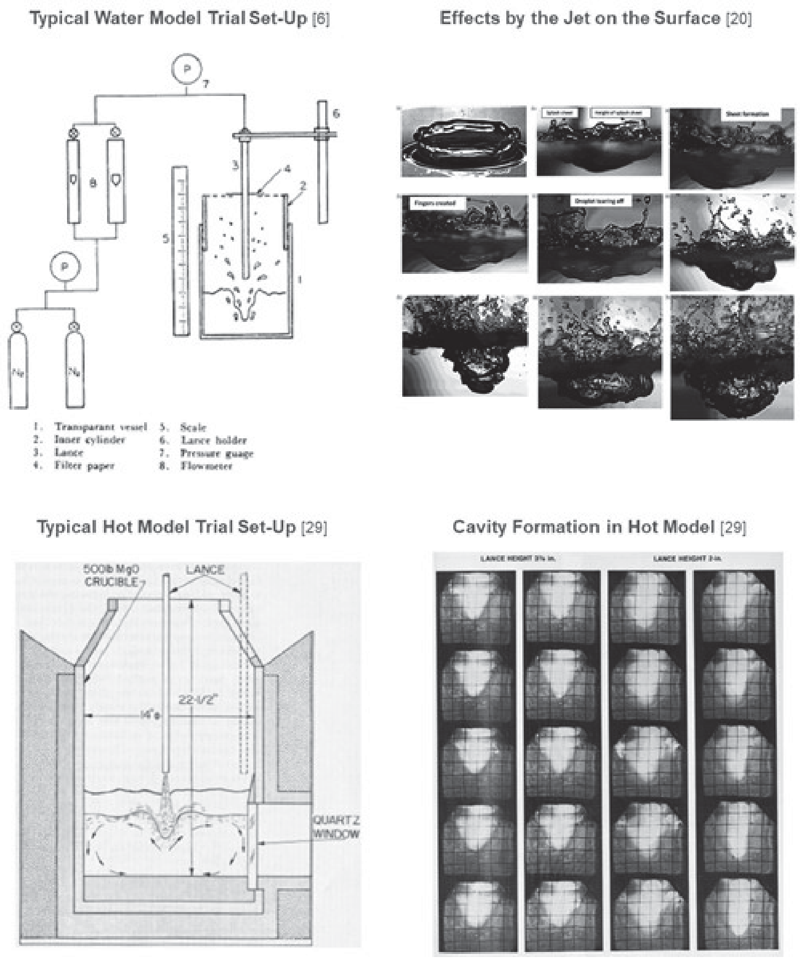


Figure 5: Penetration of an Air/Oxygen Jet into a liquid Surface [6], [20], [29]

PHYSICAL MODELLING OF THE BOF PROCESS

It is common practice to use Thermochemical mass and heat balance models to operate the furnace, Charge materials and the Oxygen amount are balanced to reach to the aimed steel composition and temperature. Even today most of these models don’t consider the physical effects of the lance blowing on the process results.

The physical effects off the Oxygen jet impinging on a liquid surface were investigated by numerous researches. In the initial stage as well as today (1954-2015) cold models are frequently used to study the effects of the jet at the bath surface, Figure 5 [1] – [27]. Only a few researchers (1967-2005) have studied the mechanism of the blow in hot models [28] – [33].

Another possibility to study flow phenomena in a BOF during blowing is CFD-(Computational Fluid Dynamics)-modelling which today is widely applied. Figure 6 shows the results from recent investigations [23], [34] - [37]. All of the cold physical approaches (water models & CFD studies) do not/incompletely consider the influence of the slag layer on top of the metal bath and the effect of the chemical reactions and the temperature at the different transition areas as described in Figure 4. Today it is well understood that the main part of the Oxidation reactions during the blow happens inside of the slag foam above the bulk metal bath. Also it is very clear that the gas volume generated by the oxidation reactions at high temperature is much higher than can be simulated in a cold water model.

Hot models have the disadvantage that in the small scale used, still the observations during the blow are limited due to the high temperature reactions and process emissions hindering the visibility of the process. Nevertheless from hot models important insight could be gathered about metal splash and droplet size and generation amount [30].

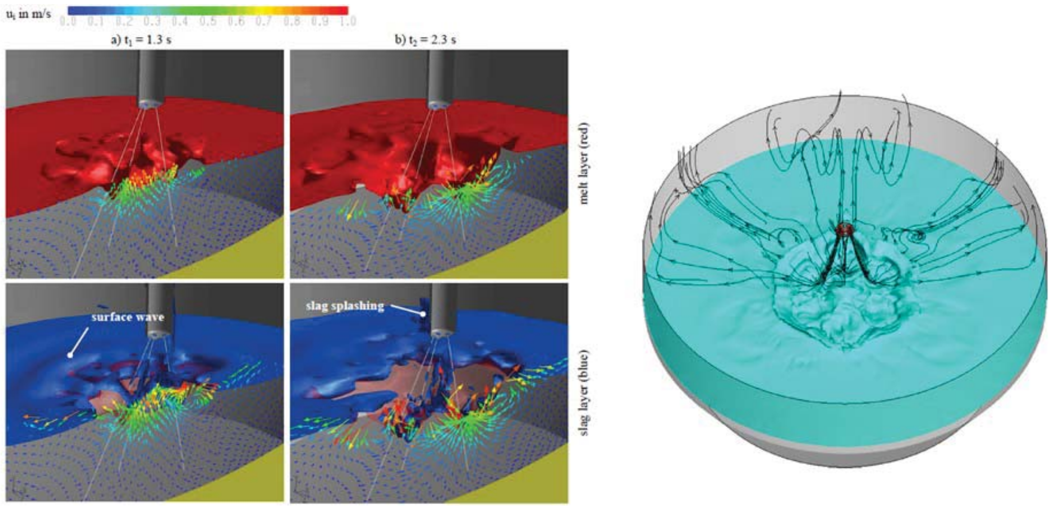


Figure 6: Modelling of Jet Penetration by CFD [24], [36]

Fundamental studies and small size lab scale trials are valuable to create fundamental understanding of the BOF process but the main question is how to "translate" this knowledge into blowing patterns for practical operational use. By application of dimensionless analysis mathematical formulas have been developed to describe the effects of the blowing parameters (flow rate, lance height and nozzle design) on the change in the transition areas between metal, slag, droplets and foam, which will be discussed next.

MATHEMATICAL DESCRIPTION OF THE JET PENETRATION

The common method to describe the effect of the Oxygen Jet on the surface of the metal bath is to calculate the so called penetration depth or L [m] which is defined as the distance of the deepest point of the cavity to the bath surface in stationary condition. In dimensionless analysis the Penetration Index PI [-] which is defined as the quotient of the penetration height L to the stationary bath height L_0 [m] is applied. The equations published in the literature have three typical formats:

1. Equations derived from dimensionless analysis of water model trials (Collins & Lubanska [1], Maia [21] and other).
2. Empiric equations derived from water/hot model investigations (Flinn [28], Ishikawa [6], Masazumi (Segawa) [8], Kai [9] and other).
3. Simplified equations derived from regressions (Lange & Koria [10], [11] and other).

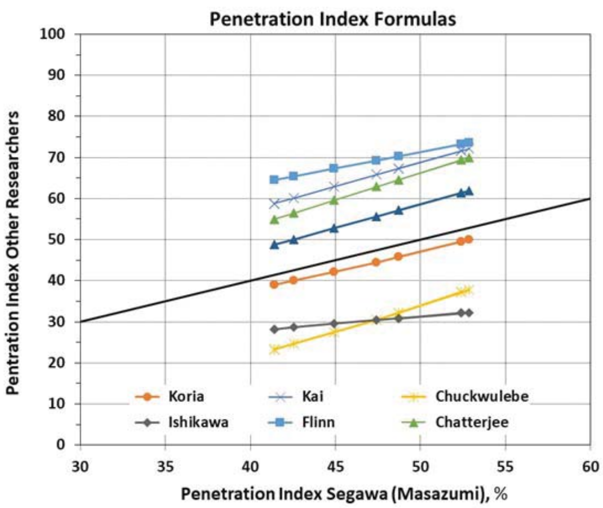
For the result comparison of the equations, discussed below, the equation of Masazumi (Segawa) [8] was chosen for reference, because this is the common equation used in many BOF-shops in North & South America. The authors believe that the approach of Kai [9] is more complete, because in his publication of 1983 [9] for the first time the relation between the Penetration Index and the mixing energy dispatched by top and also bottom stirring/blowing was discussed. The equations of Lange & Koria [10] were chosen for reference, because they have split the jet momentum in a vertical and horizontal component. With the diameter and the depth of the cavity the interface between the bulk metal and the Oxygen jet can be calculated by application of the equation for the surface area of a parabola of revolution.

MATHEMATICAL DESCRIPTION OF THE DROPLET GENERATION

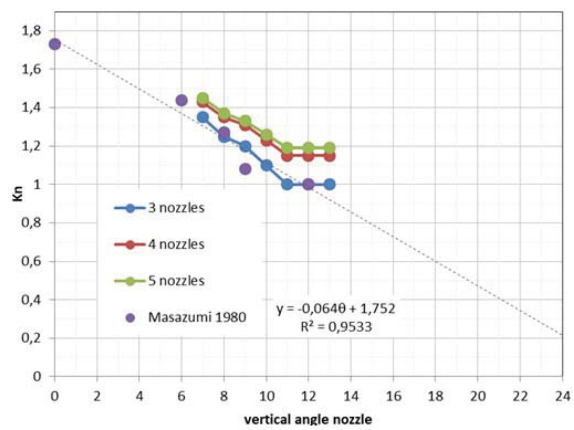
The generation of droplets and their size distribution were investigated by Lange & Koria [11] in hot model trials carried out in the mid 1980ies. In their laboratory tests they splashed out metal droplets by blowing with a top lance onto a pool of liquid metal. After cooling down the metal collected on refractory material placed around the blowing vessel they collected the solidified splashes and categorized them by screening. From this research work equations to estimate the droplets generation (metal volume cycling) and the size distribution of the droplets were developed. The surface area of the interface between the metal droplets and the slag foam can be calculated form the amount and size of the droplets by application of the equation for he surface are of a sphere. All equations used in the next Figures are listed in the Appendix.

VALIDATION OF PUBLISHED EQUATIONS

To gain more confidence as to which formula should be used for future work the equations of several researchers were used to calculate the Penetration Index for a typical BOF installation and lance design. The result is shown in Figure 7a. The Figure compares the result obtained by the standard formula for the L/L0-relation by Masazumi (Segawa) [8] and the other equations. It is obvious that some formulas show the same behavior compared to the Segawa formula, others come to different results. The best fits are the formulas of Lange & Koria [10] and Maia 2014 [21]. The formula of Kai [9] has the same inclination but comes to significant higher penetration Index numbers. A similar comparison, but with other formulas, was published by Nordquist in 2006 [33].



7a) PI-Formulas compared to Masazumi (Segawa)



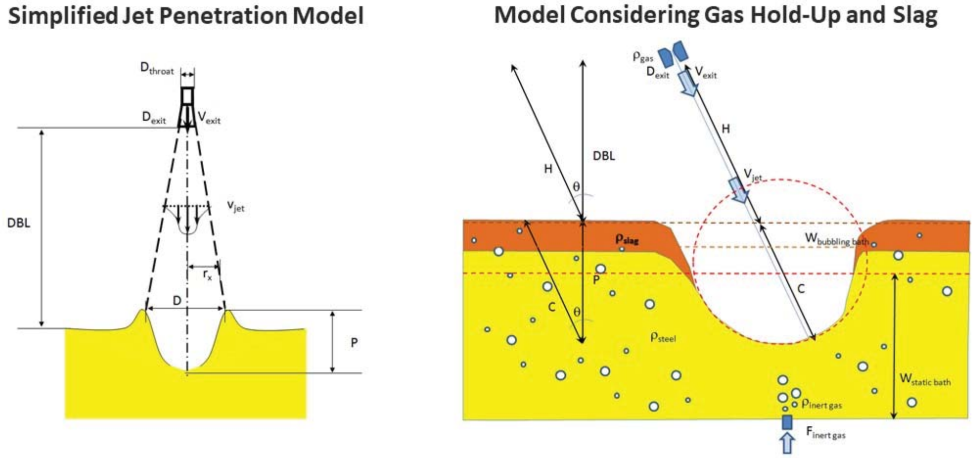
7b) Nozzle Factor

Figure 7 a/b: Validation of various equations for the Penetration Index [7], [8], [9], [11], [16], [21], [28]

In Figure 7b another problem with the formulas of several researchers is demonstrated. These formulas use an empiric tuning factor (nozzle factor) which was derived from water model trials. At the time of the trials basically 1-3 nozzle lances with inclinations of 0-12° were used in BOF operations. Today 4-6 nozzles are common operation practice and the nozzle angles vary from 14-23°. As shown in the diagram it is not possible to simply estimate the nozzle factor. So the common practice today is to freeze the nozzle factor at a constant value which of course influences the results. To eliminate this problem new water model trials would be required. Therefore the Ishikawa equation [6] and also the Masazumi (Segawa) equation [8] are not considered to be used in future work.

The next issue to be addressed for all existing equations was addressed by Maia and Tavares [27] recently. All formulas calculate the penetration index based on a static bath height L_0. But in the BOF operation the bath height is not static, it is dynamic:

1. In most of the shops the hot metal/scrap ratio varies according to price and availability. In general these changes are not compensated for the blow pattern.
2. For the L/L_0 calculation in most applications the steel bath height from the refractory drawing is used. The bath height changes with the refractory wear.
3. Oxidized metal droplets are sinking back into the melt and are being reduced by forming CO-bubbles. These bubbles decrease the metal density and increase the metal bath height.
4. When bottom stirring is applied, Ar/N_2-bubbles are released to the melt. These bubbles will decrease the metal density and increase the bath height.



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

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

Figure 8: Jet Penetration Model Modification Requirements [27]

The authors propose adapted modification of the penetration index formula which are shown on the right side of Figure 8. The influence of these effects on the results of the L/L0-theory must be further studied in water model experiments, especially the effects of the bottom stirring on the bath density.

INTERPRETATION OF PENETRATION INDEX FOR PRACTICAL USE

The discussion of the validity of the L/L_0-theory leads to the question coming up "what is the practical benefit" of the theoretical approach. The answer is obvious: the L/L_0-theory 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 flow rate changes and lance movements (lance tip nozzle design differences included). The results obtained from the laboratory trials have already been classified according to the physical effects observed in the past [8]. In Figure 9 the classical approach was more detailed and gives a classification and "translation" of the effects. Soft, medium and hard blow is differentiated by the physical effects happening during blowing. The more intensive the blow, the more intensive is the jet penetration, the splashing, the De-Carburization, but also leads to negative effects appearing such as lance, mouth and hood skulling.

Type of Blow	Oxidation	Soft	Soft-medium	Medium	Medium-hard	Hard	Heavy	Furnace and Lance Damage
L/L_0	<0,20	0,20 - ,040	0,40 – 0,55	0,55 – 0,60	0,60 – 0,75	0,75 – 0,80	0,80 – 1,00	>1,00
Blow Aspect	Oxygen jet don´t touch the static liquid bath, just create atmospheric oxidation into vessel	Small penetration	Jet penetration enough to ignition and able to start Fe oxidation and lime dissolution	Penetration applied to some DeC conditions for low P. Foaming slopping occur in this range	Penetration applied in general during DeC blow period	Strong penetration, normally for fast DeC time. Metallic slopping occur in this range	This relation is used to blow fast and same time avoids the bottom build up. Dangerous for lance tip	This range is used to specific works outside blow like burn bottom

Figure 9: Jet Penetration Effect on Blowing Behavior [27]

But this consideration, same as the general rules for blowing patterns presented in Figure 2, is more or less a general approach. Steelmakers design blow practices to follow these general rules and to achieve the penetration index suitable for their operation according to these equations such as Balajee et al. [13] and Chukwulebe et al. [16]. However, these practices are largely based on operating experience. So how to "translate" the general rules and regulations to a practical approach?

In the next Figure 10 the calculation results of the characteristic parameters for an actual industrial case blowing pattern are shown [38], [39]. In the upper graph the Oxygen flow rate [m_n^3/min], the lance height [cm], the Oxygen pressure [bar] and the resulting jet momentum [N] are shown. Since the Oxygen flow is kept constant and the lance tip design is also fixed, the pressure and the jet momentum are also constant during the blow. The lance height is changed sequentially to adapt to the different stages of the blow. In the 1st third of the blow the lance is kept high to promote slag formation and lime/dololime solution. At the estimated start of the main De-Carburization the lance is kept on the lowest position, obviously not correlated to the Si-Oxidation. After 50% of the blow the lance is significantly raised to compensate for the slag reduction. Towards the blow end the lance is driven down again to promote the final De-Carburization.

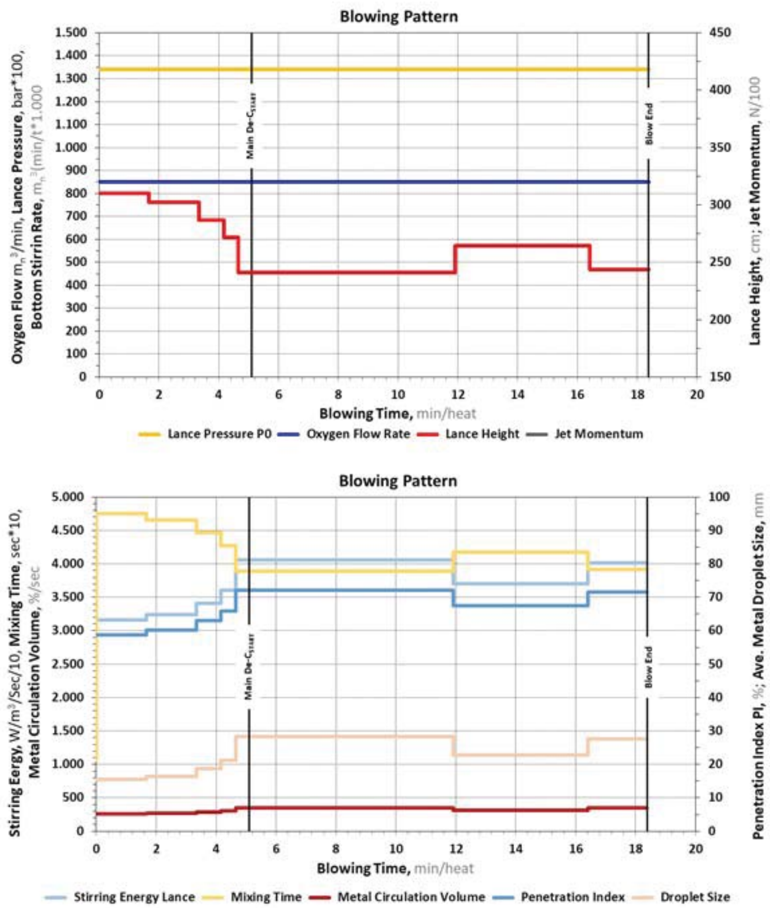


Figure 10: Results of Jet Penetration Calculation at the BOF [38], [39]

The "translation" of this blowing pattern into the characteristic formulas for jet penetration, stirring energy (just lance), mixing time, metal circulation volume and average droplet size is shown in the lower part of the diagram. Penetration index, mixing energy and also metal circulation volume follow the lance movement's direct proportional. The droplet size also follows the penetration index (PI), which the droplet size increases with PI. This means that the reaction interface of the droplets are inverse to penetration index (PI). The mixing time decreases with increasing mixing energy. From these results the predominant influence of the lance position can be estimated.

Taking this interpretation into account, the multidimensional function of the blowing tools can be reduced to two main factors, Figure 11:

1. The reaction interface of the Oxygen jet to bulk metal and
2. The reaction interface of the metal droplets in the slag emulsion above the bulk metal bath.

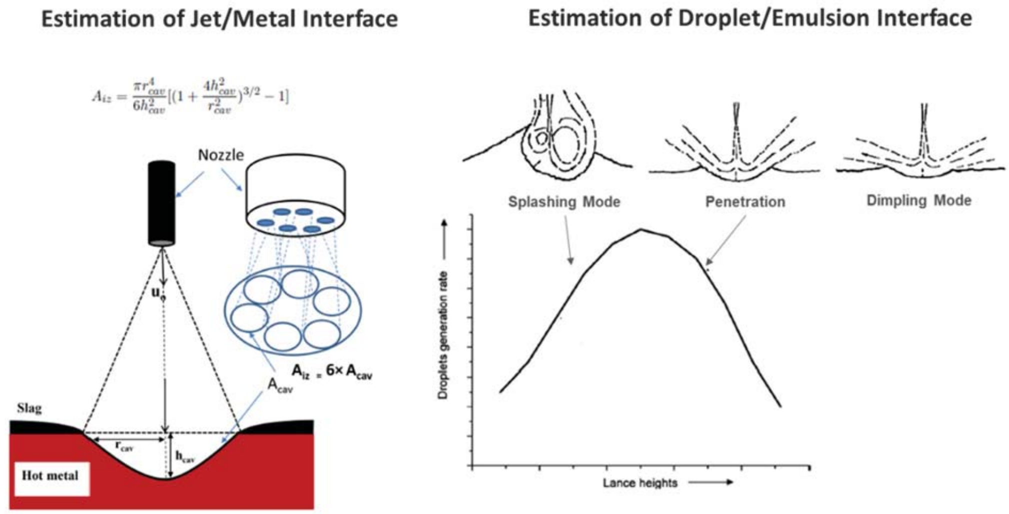


Figure 11: Estimation of Reaction Interface Changes [20], [37]

The reaction interface between the Oxygen jet and the bulk metal is created by the jet impingment to the surface created by the lance tip. The variables are clear, they are number of nozzles, nozzle inclination, nozzle throat diameter and nozzle exit diameter. These factors together with the Oxygen flow rate and the lance position above the bath create the Oxygen cavity. Of course, in real industrial conditions there will be not only one cavity but several cavities according to the number of nozzles in the lance tip. But for simplification reasons it is estimated that the surface of the multiple cavities is equal to a single cavity. The reaction surface in this case can be calculated by a simple geometrical equation.

The reaction interface between the metal droplets ejected by the jet and the slag emulsion can be estimated by the calculation of the droplet "birth rate" and the average droplet diameter. Both parameters can be calculated by the equations developed by Lange & Koria [10].

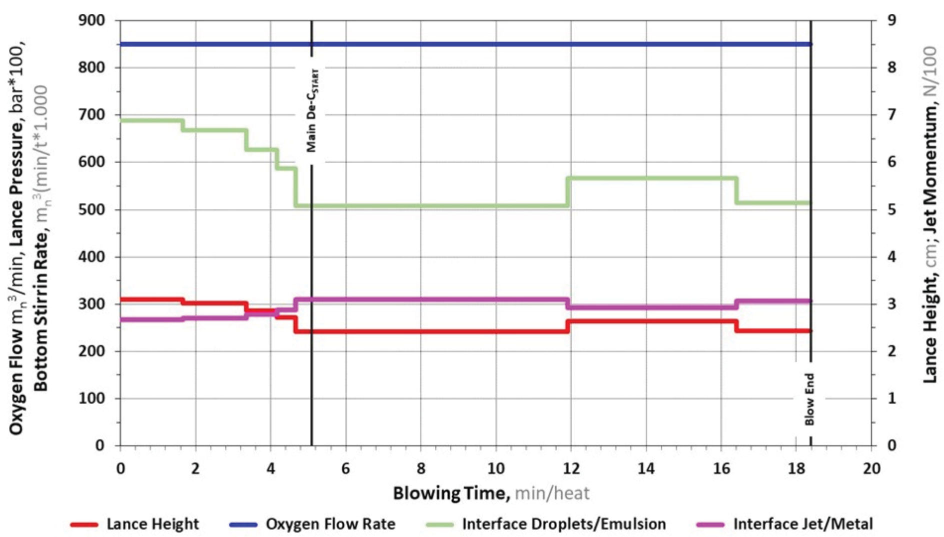


Figure 12: Blowing Pattern and Reaction Interface Changes

Again "translated" into the blowing pattern the reaction interfaces show the behavior represented in **Figure 12**. It becomes obvious that the Oxygen jet/bulk metal interface behaves inversely to the lance height but the interface droplets/emulsion behaves directly. The Figure also shows that the droplet interface is much higher (> 150 times) compared to the jet/metal interface. In practical application this indicates that lance height movements are much more efficient compared to other manipulations to control the blowing process in Oxygen steelmaking converters.

The next Figure 13 shows the effects of a real blow on measurable input and output parameters. The upper left graph shows the blowing pattern execution (no constant Oxygen flow applied). The upper right graph shows the off-gas analysis (in the stack). The black curve is the De-Carburization rate in kg Carbon/m_n^3 Oxygen. The lower left graph shows the off-gas volume and the lime, dololime and iron ore addition and the lower right side shows the estimated distribution of the blown Oxygen to the predominant reactions.

The blowing regime is similar to the blow pattern in Figure 10, but now showing real time data. The lance movement is according to the pattern, the Oxygen flow is slightly reduced in the period of slopping. The off-gas volume (including the infiltrated air) is at 220,000 m^3/h. The addition of lime, dololime and iron ore starts at roughly 90s after the start of the blow. The off gas composition is shown in the upper right graph. The Nitrogen content of the gas is decreasing from air level (69%) to blow level (40%) after 35% of the blow. After 80% of the blow it raises back to air level which is almost reached at the end of the blow. CO starts increasing after O_2 is gone and reaches up to 40% in the period when the lance is raised. At the point when O_2 comes up at the end of the blow CO_2 is passing through a maximum which is typical for the blow. This means that at this point of the blow all gas coming from the vessel mouth is burnt by the infiltrated air to CO_2.

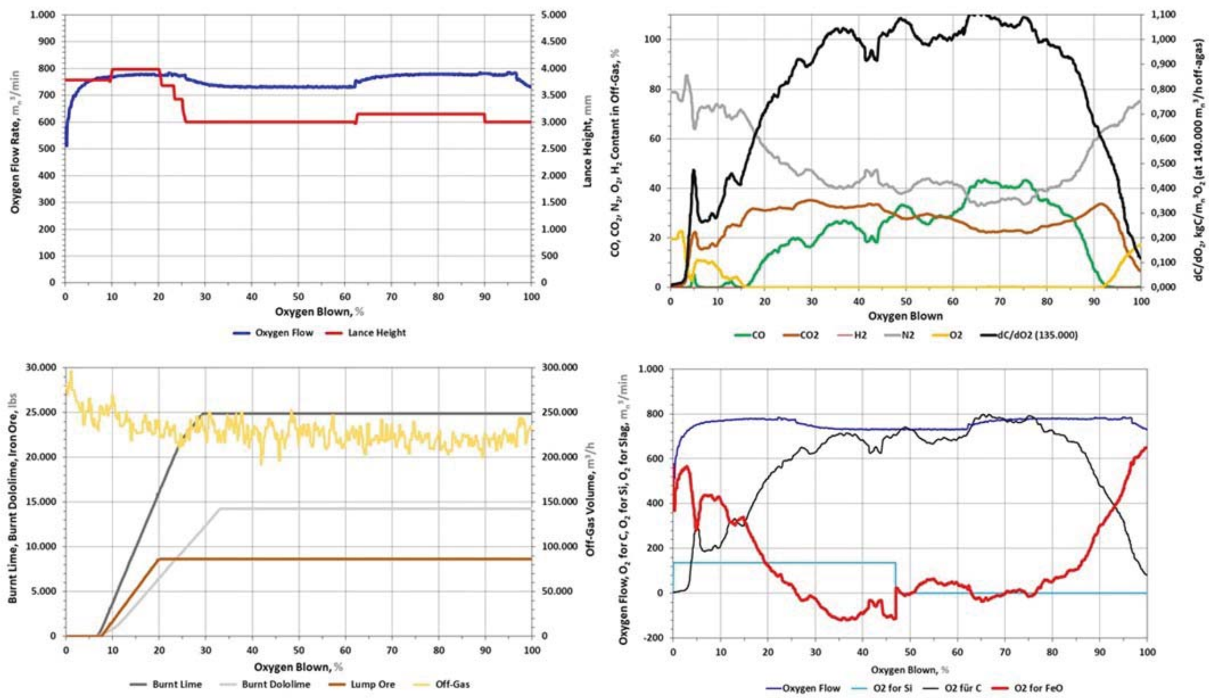


Figure 13: Blowing Pattern and Slag/Gas Reactions

In the lower right diagram it can be clearly observed, that the red curve, the slag (%FeO) curve turns into negative values right at the end of the De-Siliconization. In our interpretation of the process this effect is induced by slag reduction of (%FeO), (%MnO) and (%P_2O_5). The slag dries out. If the (%FeO) content during this period falls below a level of 10% the bulk slag will become solid. Gas is accelerated under the slag but cannot pass through. When the gas pressure under the solid slag is high enough to break the slag layer it comes to an eruptive reaction, well known as heavy slopping. When the slag dries out, this can also lead to spitting and skulling on the lance and furnace mouth.

The heavy slopping effect must not be confused with the overflow of liquid foaming slag because the total volume simply is too big to keep the material in the vessel. This overflow happens because the consistency of the slag is too viscous and the gas generation is already too high. It can be controlled by the lance position. To control the slag dry out the lance movement down to the lowest position must be delayed and adapted to the end of the De-Siliconization, which is at 45% of the blow in case a constant Oxidation rate for Silicon is estimated (in reality the Silicon Oxidation rate will not be constant. But the variation according to own calculations is less than 10%. So for this demonstration it was estimated to be constant).

Balajee et al. [13] reviewed the lance tip nozzle theory and design and conducted BOF plant trials increasing the nozzle angle from 10 to 13 degrees for improved slag formation and mixing. The lance and mouth skulling was decreased and allowed the BOF shop to utilize low silicon hot metal without adversely affecting the furnace lining wear. A wider nozzle angle reduced the jet overlap, minimizing the metal droplets hitting the furnace mouth and the lance surface that cause skulling. The lance life increased with the nozzle design modification, based on using the nominal BOF furnace pressure as the nozzle exit pressure and modifications to the blow profile to establish the desired L/Lo penetration index range. The turndown performance (C and temperature) was improved.

Slopping was studied for two BOF steel shops by Chukwulebe, Balajee et al. [16]. Slopping Index (SI) was correlated with a relative L/Lo [from the slopping Index (SI) and the ratio of the furnace volume to charge volume (V)], lance height (LH) and Oxygen Flow rate (OFR). A fuzzy logic model was developed using the major slopping variables, such as the HM Si, FeO/C, and V. From the plant trials and data analysis, lance height and oxygen flow rate were adjusted to effectively control or minimize slopping during the slop period (30% to 50% of the blow).

The effect of overflow of foamy slag out of the vessel was also studied by Guo and coauthors in their publication series about the blow model improvements in a US-BOF shop [38], [39], [40]. Other than explained before their conclusion is, that excessive De-carburization induced from bad lance profile and too high (%Fe_xO) content are the reason for the overflow. This conclusion does not consider the change in the physical slag properties related to the (%Fe_xO) content and the slag basicity (%CaO)/(%SiO_2) which is in the "foamy slag" range of 1.5 during the complete first half of the blow. Nevertheless also this phenomena is not completely understood and must be studied in future work.

CONCLUSIONS AND FUTURE WORK

From the discussion of the blow physics and how to translate them into practical blowing patterns it can be concluded:

1. The Jet Penetration equation of Koria and Lange is recommended as it does not use the K factor and takes into account the jet momentum and mixing energy.
2. The comparison of the blow physics with real time operation results clearly demonstrates the predominant effect of lance height movements on the behavior of the bulk liquids and the emulsion during blowing. A complicated system of foam height control by consistency/viscosity control, bulk slag composition/fluidity control and CO-gas generation control must be balanced during blowing.
3. It could be demonstrated that the metal droplet generation characterized by the amount and average size of the droplets and the reaction interface created by the droplets is the main effect produced from the Oxygen jet and the lance position. The reaction interface metal droplets/emulsion is significantly higher compared to the direct reaction interface Oxygen jet/bulk metal. By the lance movements the metal droplets/emulsion interface is varied by half.

For future work the authors recommend:

1. Modeling and real plant studies are needed to define the K factor for the nozzle angles >12 in jet penetration equations, including in the Masazumi (Segawa) equation, as currently, many BOFs use 14 to 23 degree nozzle angles which was not common at the time the equations were published. Further, the effect of the number of the nozzles on the K factor should also be evaluated, taking into account the jet separation or the jet overlap phenomena.
2. The influence of the gas bubbles inside the metal bulk (generated from droplets falling back into the bath and from bottom stirring) on the metal density and the bath level must be studied.
3. In this study, the effect of bottom stirring on droplet birth rate was not discussed. Although, droplet generation (birth rate) was investigated by other researchers, future modeling of the BOF process should focus on this effect. The metal droplet/emulsion interface influences the oxygen distribution between gas and slag and dependence on dynamic effects such as hot metal conditions (Silicon content) and vessel profile during the campaign should be topics of study.

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APPENDIX

Various Jet Penetration Equations used in Figure 7 and equations used to calculate the stirring energy, the metal circulation and average droplet size in the Figures 10 and 12.

28. FLINN, R. A., PEHLKE, R. D., GLASS, D. R., HAYS, P.O.: "Transactions of the Metallurgical Society of the American Institute of Mechanical Engineering", 1967, 239 (11), P. 1176.

$$\boldsymbol{h_n = 1,5 \cdot \frac{P_0 \cdot d_t}{\sqrt{h_L}}} \qquad [m] \qquad [28] \qquad (1)$$

Where: $\boldsymbol{h_n}$ = penetration depth of the jet in [m], $\boldsymbol{P_0}$ = Oxygen pressure at nozzle entrance in [10^5 N/m^2], $\boldsymbol{d_t}$ = nozzle throat diameter in [m], $\boldsymbol{h_L}$ = distance of nozzle to bath surface in [m].

6. ISHIKAWA, H., MIZOGUCHI, S., SEGAWA, K.: "A Model Study to Jet Penetration and Slopping in the LD Converter", Tetsu-to-Hagane, 1972, v.58, n.1, p. 76-84.

$$\boldsymbol{h_{n_0} = 1,67 \cdot \left(\frac{V_{O_2}}{d_t}\right)^{(2/3)}} \qquad [m] \qquad (2)$$

$$\boldsymbol{h_n = h_{n_0} \cdot e^{\left(-1,77 \cdot \frac{h_L}{h_{n_0}}\right)}} \qquad [m] \qquad (3)$$

Where: $\boldsymbol{h_n}$ = penetration depth of the jet in [m], $\boldsymbol{h_{n_0}}$ = penetration depth of the jet at lance height penetration depth of the jet in [m], $\boldsymbol{\dot{V}_{O_2}}$ = Oxygen flow rate [10^5 N/m^2], $\boldsymbol{d_t}$ = nozzle throat diameter in [m], $\boldsymbol{h_L}$ = distance of nozzle to bath surface in [m].

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$$\left(\frac{h_n}{h_L}\right) \cdot \left(\boldsymbol{1} + \frac{h_n - X}{h_L}\right)^{\boldsymbol{2}} = \left(\frac{K'_4}{\pi}\right) \cdot \left(\frac{\dot{m}}{\rho_l \cdot g \cdot h_L{}^3}\right) \cdot \left(\frac{P_0}{P_{a_{real}}}\right) \qquad [-] \qquad (1)$$

Where: $\boldsymbol{h_n}$ = penetration depth of the jet in [m], $\boldsymbol{h_L}$ = distance of nozzle to bath surface in [m], $\boldsymbol{X}$ = *f*actor supersonic core length ($\boldsymbol{X}$ = 7 · $\boldsymbol{d_E}$) in [-], $\boldsymbol{d_E}$ = nozzle exit diameter in [m], $\boldsymbol{K'_4 = 2K_1{}^2}$ in [-], K_1 = slope of the dimensionless regression (= 100) in [-], $\boldsymbol{\dot{m}}$ = impact force of the gas-jet in [N], $\boldsymbol{\varrho_l}$ = density of the liquid in [kg/m^3], $\boldsymbol{g}$ = acceleration of gravity in [m/s^2], $\boldsymbol{P_0}$ = Oxygen pressure at nozzle entrance in [10^5 N/m^2], $\boldsymbol{P_{a_{real}}}$ = ambient pressure inside of the blowing converter in [10^5 N/m^2].

8. MASAZUMI (Nippon Steel Corporation): "Converter steelmaking process" – European Patent specification No. 0017963 B1, 15.04.1980 (this equation is also called **Segawa** equation, published in a Japanese book from 1977 which is not available)

$$\boldsymbol{h_n = A_1 \cdot e^{\left(\frac{-0,78 \cdot h_L}{A_1}\right)}} \qquad [mm] \qquad (4)$$

$$\boldsymbol{A_1 = 63,0 \cdot \left(\frac{k \cdot \dot{V}_{O_2}}{60 \cdot n \cdot d_E}\right)^{2/3}} \qquad [mm] \qquad (5)$$

Where: $\boldsymbol{h_n}$ = penetration depth of the jet in [m], $\boldsymbol{A_1}$ = auxiliary variable, $\boldsymbol{h_L}$ = distance of nozzle to bath surface in [m], $\boldsymbol{\dot{V}_{O_2}}$ = Oxygen flow rate [10^5 N/m^2], $\boldsymbol{k}$ = nozzle constant (1,056 for multiple hole lances), $\boldsymbol{n}$ = number of nozzle in lance tip [n], $\boldsymbol{d_E}$ = nozzle exit diameter in [m].

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$$h_n = 0,00999 \cdot \left[\frac{\dot{V}_{O_2}}{(n \cdot d_t)}\right]^{2/3} \cdot exp\left[-780 \cdot \frac{h_L}{\left\{9,99 \cdot \left[\frac{\dot{V}_{O_2}}{(n \cdot d_t)}\right]^{2/3}\right\}}\right] \qquad [m] \qquad (6)$$

Where: h_n = Penetration depth of the jet in [m], $\dot{V}_{O_2}$ = Oxygen flow rate in [m_n^3/min], n = number of nozzles in lance tip in [n], d_t = nozzle throat diameter [m], h_L = distance of nozzle to bath surface [m].

10. S.C. KORIA, K.W. LANGE: "Penetrability of impinging gas jets in molten steel bath", Steel Research 58 (1987), No. 9, P. 421–426.

$$\dot{M}_t = \frac{0,7854 \cdot 10^5 \cdot n \cdot d_t^{2} \cdot P_{a_{real}} \cdot \left(1,27 \cdot \frac{P_0}{P_{a_{real}}} - 1\right)}{\rho_{LS} \cdot g \cdot h_L^{3}} \qquad [-] \qquad (7)$$

The vertical component of $\dot{M}_t$ ist he penetration depth:

$$\frac{h_n}{h_L} = 4,469 \cdot \dot{M}_h^{0,66} \qquad [-] \qquad (8)$$

$$\dot{M}_h = \dot{M}_t \cdot \frac{\cos\theta}{n} \qquad [-] \qquad (9)$$

The horizontal component of $\dot{M}_t$ is the diameter of the cavity:

$$\frac{d_n}{h_L} = 2,813 \cdot \dot{M}_d^{0,282} \qquad [-] \qquad (10)$$

$$\dot{M}_d = M_t \cdot \sin\theta \qquad [-] \qquad (11)$$

Where $\dot{M}_t$ = Dimensionless jet- impact in [-], n = number of nozzles in lance tip [n], d_t = nozzle throat diameter [m], $P_{a_{real}}$ = ambient pressure inside of the blowing converter [10^5 N/m^2], P_0 = Oxygen pressure at nozzle entrance in [10^5 N/m^2], P_{LS} = density of the liquid in [kg/m^3], g = acceleration of gravity [m/s^2], h_L = distance of nozzle to bath surface [m], θ = nozzle angle in lance tip [°].

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$$h_{n_0} = \frac{4 \cdot m_{LS}}{\left[\rho_{LS} \cdot \pi \cdot \left(d_F^{2}\right)\right]} \qquad [m] \qquad (12)$$

$$h_n = \frac{63,0 \cdot \left[\frac{k \cdot \dot{V}_{O_2}}{h_L \cdot d_E}\right]^{0,6667}}{e^{\frac{0,78 \cdot h_L}{h_{n_0}}}} \qquad [m] \qquad (13)$$

Where: h_n = penetration depth of the jet in [m], k = nozzle constant (1,056 for multiple hole lances), $\dot{V}_{O_2}$ = Oxygen flow rate [m_n^3/min], h_L = distance of nozzle to bath surface in [m], d_E = nozzle exit diameter in [m], m_{LS} = steel weight [kg], ρ_{LS} = steel density [t/m^3], d_F = furnace diameter [m].

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$$\frac{\pi \cdot \rho_g \cdot v_m^{2} \cdot d_E^{2} \cdot \cos\theta \cdot n}{4 \cdot \rho_{LS} \cdot g \cdot h_L^{3}} = \frac{2}{K^2} \cdot \frac{h_n}{h_L} \cdot \left(1 + \frac{h_n}{h_L \cdot \cos\theta}\right)^2 \qquad [-] \qquad (14)$$

Where: ϱ_g = gas density at nozzle exit in [kg/m^3], v_m = gas velocity at nozzle exit in [m/s], d_E = nozzle exit diameter in [m], θ = nozzle angle in lance tip in [°], $\mathbf{n}$ = number of nozzles in lance tip [n], ϱ_{LS} = density of liquid steel in [kg/m^3], g = acceleration of gravity in [m/s^2], h_L = distance of nozzle to bath surface in [m], K = empiric constant [-], h_n = penetration depth of the jet in [m].

11. S.C. KORIA, K.W. LANGE: "Estimation of drop sizes in impinging jet steelmaking", Ironmaking and steelmaking V.13 (1986) No.5 P. 236-240.

$$\frac{\dot{M}_V}{m_{HM}} = 8046,86 \cdot \left[\frac{d_t^{2} \cdot P_{a_{real}} \cdot \left(1,27 \cdot \frac{P_0}{P_{a_{real}}} - 1\right) \cdot \cos\theta}{\rho_{LS} \cdot g \cdot h_L^{3}}\right]^{0,4} \quad [-] \qquad (8)$$

$$d_{ave} = 0,2 \cdot 5,51 \cdot 3\ 10^{-3} \cdot \left[\frac{10^6 \cdot n \cdot P_{a_{real}} \cdot \left({d_t^2}/{h_L^2}\right) \cdot \left[1,27 \cdot \left(\frac{P_0}{P_{a_{real}}} - 1\right) \cdot \cos\theta\right]}{n}\right]^{1,206} \quad [\mathrm{m}] \qquad (9)$$

Where $\dot{M}_v$ = Total amount of droplets in [kg/heat], m_{MH} = hot metal weight in [t/heat], d_t = nozzle throat diameter [m], $P_{a_{real}}$ = ambient pressure inside of the blowing converter [10^5 N/m^2], P_0 = Oxygen pressure at nozzle entrance in [10^5 N/m^2], θ = nozzle angle in lance tip [°], ρ_{LS} = density of the liquid in [kg/m^3], g = acceleration of gravity [m/s^2], h_L = distance of nozzle to bath surface [m], d_{ave} = average diameter of droplets in [m], n = number of nozzles in lance tip [n].

The surface area between the bulk metal and the Oxygen jet can be calculated by application of the equation for the surface area of a parabola of revolution. The surface area of the interface between the metal droplets and the slag foam can be calculated form the amount and size of the droplets by application of the equation for he surface are of a sphere.