Comparison of the Various Cavity Depth or Jet Penetration Index Formulae for Blowing in a BOF with Bottom Stirring*

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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 depths of penetration equations, and recommend the most feasible equation(s) to determine the lance gap to use during the oxygen blow. This paper reviews how to translate the L/L0 in comparison with authors and yours considerations about nozzles parameters with respect to lance stirring, bottom stirring and slag layer patterns.

Keywords: BOF/LD Converter, penetration depth L; liquid steel bath height L0; lance height; oxygen flow rate; lance tip; Oxygen nozzles.

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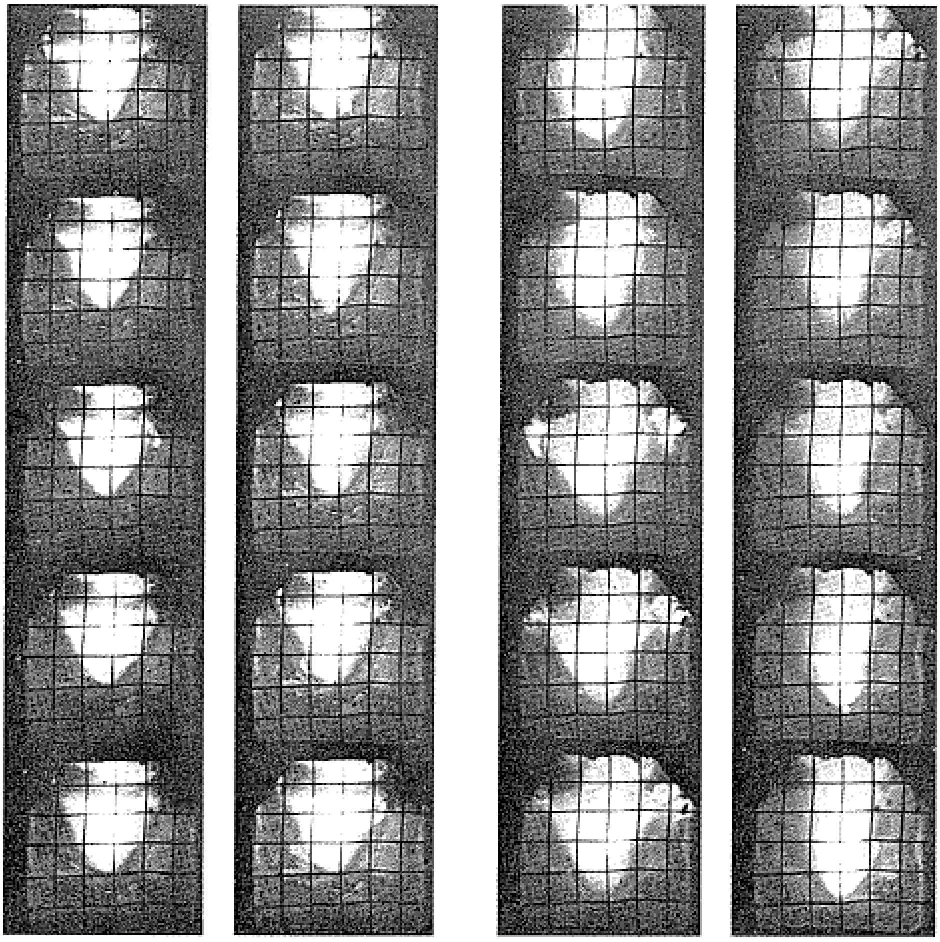
1. INTRODUCTION

Reactors that produce molten steel, such as BOF, EAF and others have a growing tendency for studies that allow defining the penetration depth of the oxygen jet into the bath and the ability of moving this mass in order to maximize the gas efficiency and reduce the process time. One of the first studies was developed using hot models like shown for Sharma *et al*[1] at figure 1.



(a) (b)

Figure 1 – Photograph of the observed penetration of an oxygen jet into a molten iron pool as reported by Sharma et al[1]: a) lance height 98,4mm and b) lance height 50,8mm.

The energy transfer mechanism through mass transfer has been known for half a century, however its use in practical applications and new developments using computational simulations have increased in the last 15 years.

2. DEVELOPMENT

a. METHODS

The methodology consisted at review papers with jet penetration calculations. Afterwards, all equations were made unit adjustments to permit compare the results and finally was choose a BOF for reference considering top and bottom blow and applied the equations over a typical blow profile.

The penetration index (PI) is the depth of the cavity divided by the depth of the water/metal bath reference.

The formulas were calculated based on the lance design, vessel design, blowing pattern of the same converter parameters like shown at Table I.

Table I - Industrial parameter of BOF used to compare jet penetration equations for L/Lo.

Parameter	PLANT 1
Nozzle throat diameter [m]	0.039
Nozzle exit diameter [m]	0.050
Number of nozzles [#]	5
Angle [degrees]	14
Oxygen flow [Nm^3/h]	51430
Static liquid bath [m]	1.78
Bottom tuyères [#]	6
Flow per tuyère [Nm^3/h/tuyére]	60
Slag rate [kg/t]	100
Steel mass [kg]	250000
BOF trunnion diameter [m]	6.1

b. DISCUSSION AND ANALYSES

i. Math Model and Industry Application

The question what happens when the jet generated by an oxygen lance hits the surface of a metal bath was investigated and simulated by many authors in the past.

They simulated the blowing process in water models or small scale hot models and proved that the jet produces a cavity on the water/metal surface. They used similarity analysis or regressions to model the shape of the cavity by its depth and width.

Masazumi[2] (LD-OB patent) for the first time shown consequence of different penetration indexes on the blowing behavior, like defined at table II.

Table II – Penetration Index and blowing phenomena.

Type of Blow	soft	soft - medium	medium	medium - hard	hard	max
L/L_0	< 0,40	0,40 - 0,55	0,55 - 0,60	0,60 - 0,75	> 0,75	0,80
Blowing Phenomena	slopping	lance skull & violent slopping			mild slopping	

The extra range was necessary due effects incorporated into some equations like: number of nozzles more than 04, vertical angle, bottom blow, slag layer behavior and effect of blowing phenomena, shown at table III.

Table III – Reviewed Penetration Index and blowing phenomena.

Type of Blow	Oxidation	Soft	Soft-medium	Medium	Medium-hard	Hard	Heavy	Furnace and Lance Damage
L/L_o	<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

Formulas calculated in this comparison are published by Flinn *et al*[3], Chatterjee[4], Ishikawa and Segawa[5], Masazumi[2], Kai *et al*[6], Koria & Lange[7] and Maia *et al*[8-10], Szekely & Themelis[11], Chukwulebe, Balajee *et al*[12], Alam *et al*[13], Meidani *et al*[14]. The figure 2 shows the results of various formulas compared to the formula of Kai *et al*[6] by Penetration Index %.

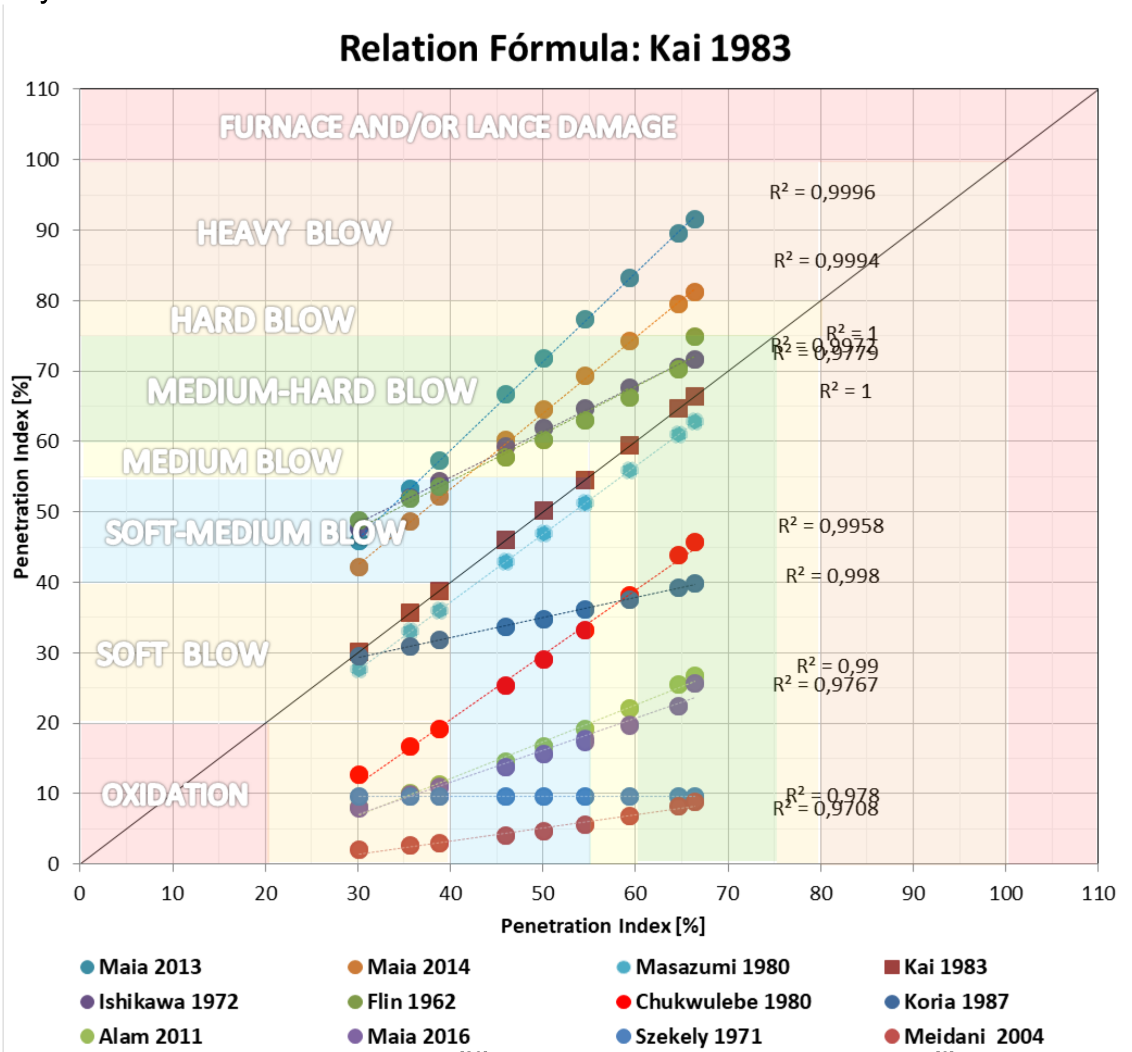


Figure 2 - The penetration index (PI)[20] - the cavity depth divided by Kai *et al*[6] cavity depth reference.

The formulas were calculated based on the lance design, vessel design, blowing pattern of the same 300t converter LD-OB or BOF. All equations did show good linear correlation. The reference line used was Kai *et al* [6] work. For these equations, curves were extrapolated to cover all ranges

In the Szekely equation, lance distance was used to project area from divergent angle from nozzles and index penetration results did not reflect appropriately over jet penetration, looking like constant. Meidani *et al* [14]. worked with coherence jets. The factor K found was around 10. In this study, were not considering the coherence effects, this is the reason to low value of penetration index. In these experiments, factor K means resistances to transfer energy from exit nozzles to the liquid bath that affect jet penetration. The K factor was constant equal 8 for fast application into industries. Cold model experiments [8-10] had variations at factor k, between 3 to 8, as function of number of nozzles, vertical nozzle angle, static slag layer and total bottom flow. Respecting constant values for each author, equations and converting values had adequate for appropriate units. Following one of these equations, were generate huge amount of blow profiles like example shown in figure 3.

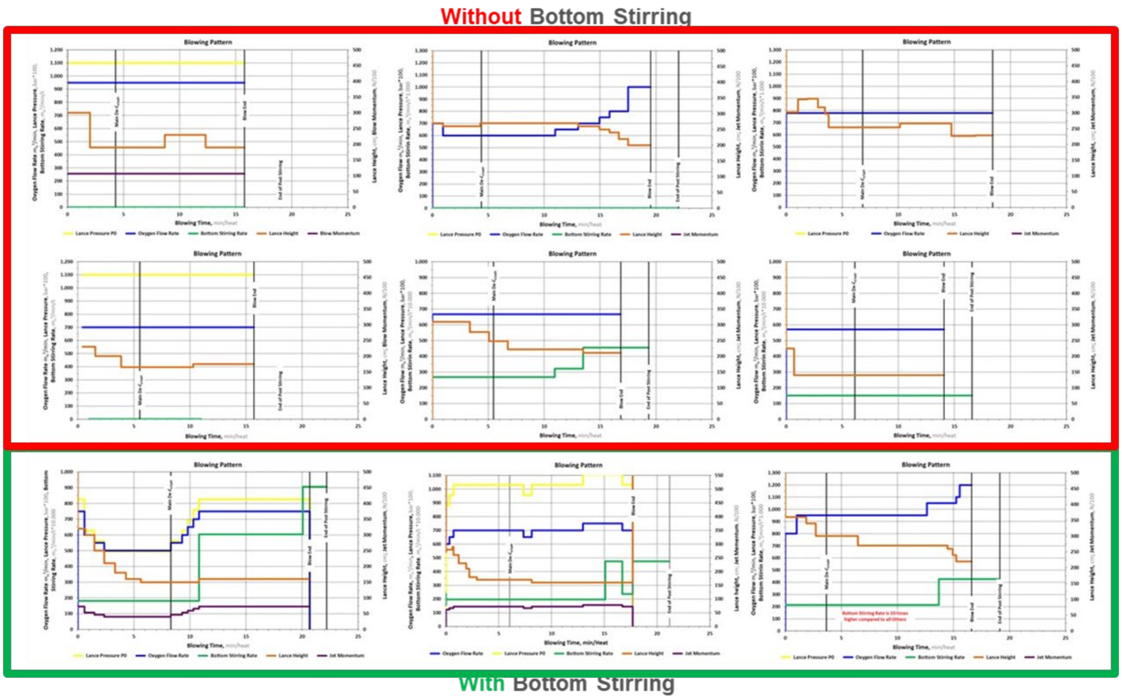


Figure 3 – Examples of blow profile with and without bottom stirring[15].

ii. Ishikawa and Segawa and Masazumi Formula Discussion

Chukwulebe, Balajee *et al* [12] in their paper about slopping control in the BOF from 2004 referred to the Ishikawa and Segawa[5] formula 1972. But they used the Masazumi (NSC) formula which was published in the LD-OB patent from 1980. The Formulas are different and come to a different PI.

Ishikawa, Masazumi and Chukwulebe equations using to converter number of nozzles and diameter to an equivalent diameter and this included a specific factor “K” and “Kn” in acording with equation (1) for Ishikawa and Segawa[5] and equation (2) for Masazumi[2] and Chukwulebe, Balajee *et al* [12].

$$d^{*} = \sqrt{3} \cdot k\, d_t \qquad \text{[m]} \qquad (1)$$

$$d^{*} = n * \frac{dt}{k_n} \qquad \text{[mm]} \qquad (2)$$

Where: "d_t" - nozzle throat diameter, "d*" – modified nozzle throat diameter, "*k*" – Ishikawa nozzle factor, "k_n" – Masazumi and Chukwulebe nozzle factor.

Ishikawa and Segawa[5] developed the nozzle factor **k** based on lance tip angles of 0°, 2,5° and 5° like shown in figure 4.

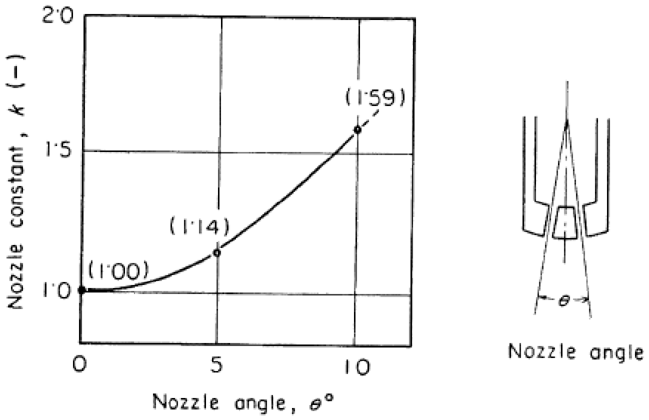


Figure 4 – Nozzles constant "k" for vertical angle until 10° by Ishikawa and Segawa[4].

When compared equation (1) and figure 4 is it important observe when d* = dt the result is k = 0,577. But k should be definitely > 1 according to the figure 3. If one uses a regression to interpolate k_n get weight too high. So this formula cannot be used without reading the Japanese paper in detail.

Masazumi[5] and Chukwulebe, Balajee *et al* [12].by equation 2 establish K_n factor for vertical angles reached until 12 degrees, typical angle for 04 nozzles lance tip. The results are shown at table IV.

Table IV — Nozzles constant "k_n" for vertical angle until 12°.

θ°	0	6	8	10	12
k	1.73	1.44	1.27	1.08	1.00

The lance tip factor "k_n" is a characteristic number for each lance tip design, which represents the blowing behavior of the different lance tips and must be evaluated by laboratory physical trials. Since at the time (1980) when the patent was published in Japan the blow with nozzle angles higher than 12° obviously was not applied, the K-numbers in the Table IV are limited to 12°. Therefore the K-numbers for the blowing angles of 14°, 17°, 20° and 23° were interpolated or kept constant after 10° vertical angle[16], as shown in the figure 5.

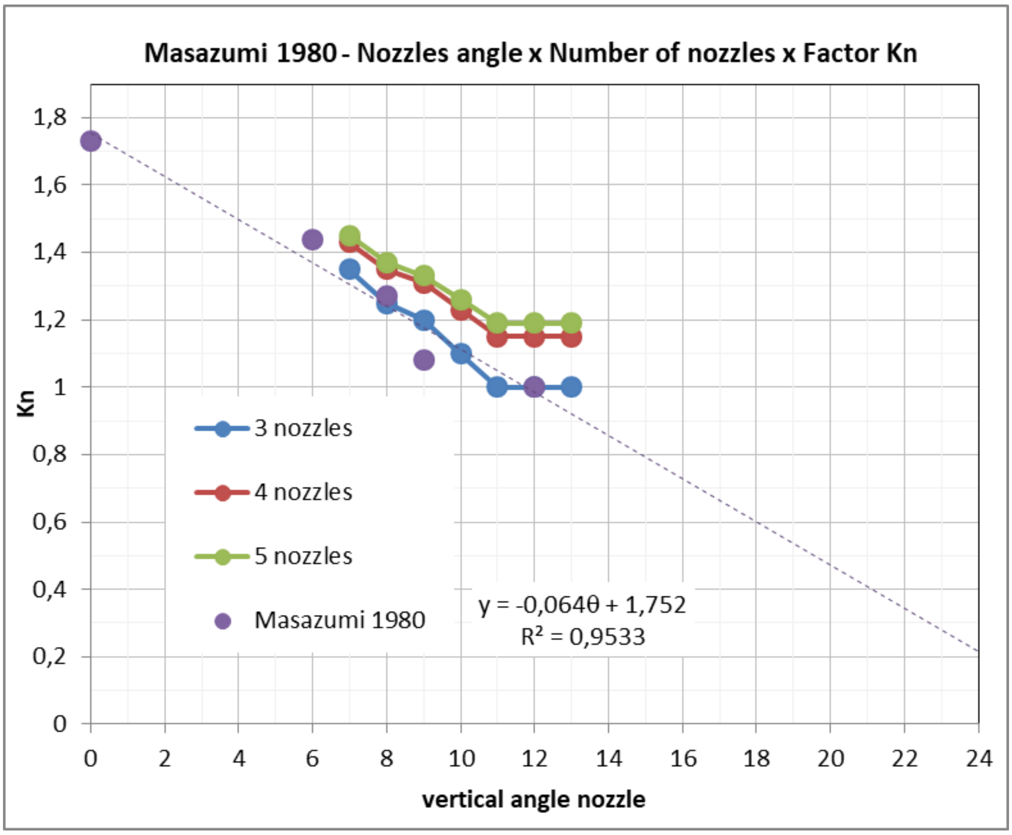


Figure 5 – Factor Kn as function of number of nozzles.

In penetration index (PI) showed in figure 2, the nozzle factor used was k=1,19 that correspond to five nozzles lance tip in according with figure 5 for 05 nozzles and angle more than 10^o.

With this factor the results of Masazumi[2], show a similar characteristic compared to the results of Kai.

According to Ishikawa and Segawa[5], the penetration depth of the oxygen jet depends on converter geometry, lance tip design, metal bath geometry and Oxygen flow rate. The simplified formulas used are:

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

$$h_n = h_{n_0} \cdot e^{\left(-1,77\frac{h_L}{h_{n_0}}\right)} \quad [m] \quad (4)$$

Where:"h_{n_0}" - Penetration depth h_n at lance height when $h_L = 0$ [m]; "h_n" - Depth of the cavity generated by the Oxygen jet; "$\dot{V}_{O_2}$" - Oxygen flow rate [Nm^3/min]; "h_L" - Lance height [m]; "d_t" - nozzle throat diameter.

Ishikawa and Segawa[5], Masazumi[2] and Chukwulebe, Balajee *et al* [12] equations defined "h_{n0}" like jet penetration when lance distance to bath is equal zero. After this first calculation, penetration is determined for various lance heights and then penetration index using this value. For all others authors, it is used "**Lo**" to refer height of static liquid bath.

In Masazumi[2] papers (Nippon Steel Corporation) dated from 1980, the patent publication compares the benefits of the LD-OB process to the standard LD-operation with and without bottom stirring. The simplified formulas used are:

$$h_n = A_1 \cdot e^{\left(\frac{-0,78 \cdot h_L}{A_1}\right)} \quad \text{[mm]} \qquad (5)$$

$$A_1 = 63,0 \cdot \left(\frac{k_n \cdot \dot{V}_{O_2}}{60 \cdot n \cdot d_E}\right)^{2/3} \quad \text{[mm]} \qquad (6)$$

Where: "h_n" - Depth of the cavity generated by the Oxygen jet [mm], "$\dot{V}_{O_2}$" - Oxygen flow rate[Nm^3/min]; "h_L" - Lance height [mm], "A_1" - Auxiliary variable, "n" – Number of nozzles in the lance tip, "d_t" - nozzle throat diameter, "d*" – modified nozzle throat diameter, "k_n" – Masazumi and Chukwulebe nozzle factor.

The figure 6 shows the results of various formulas compared to the formula of Masazumi[2] by Penetration Index %.

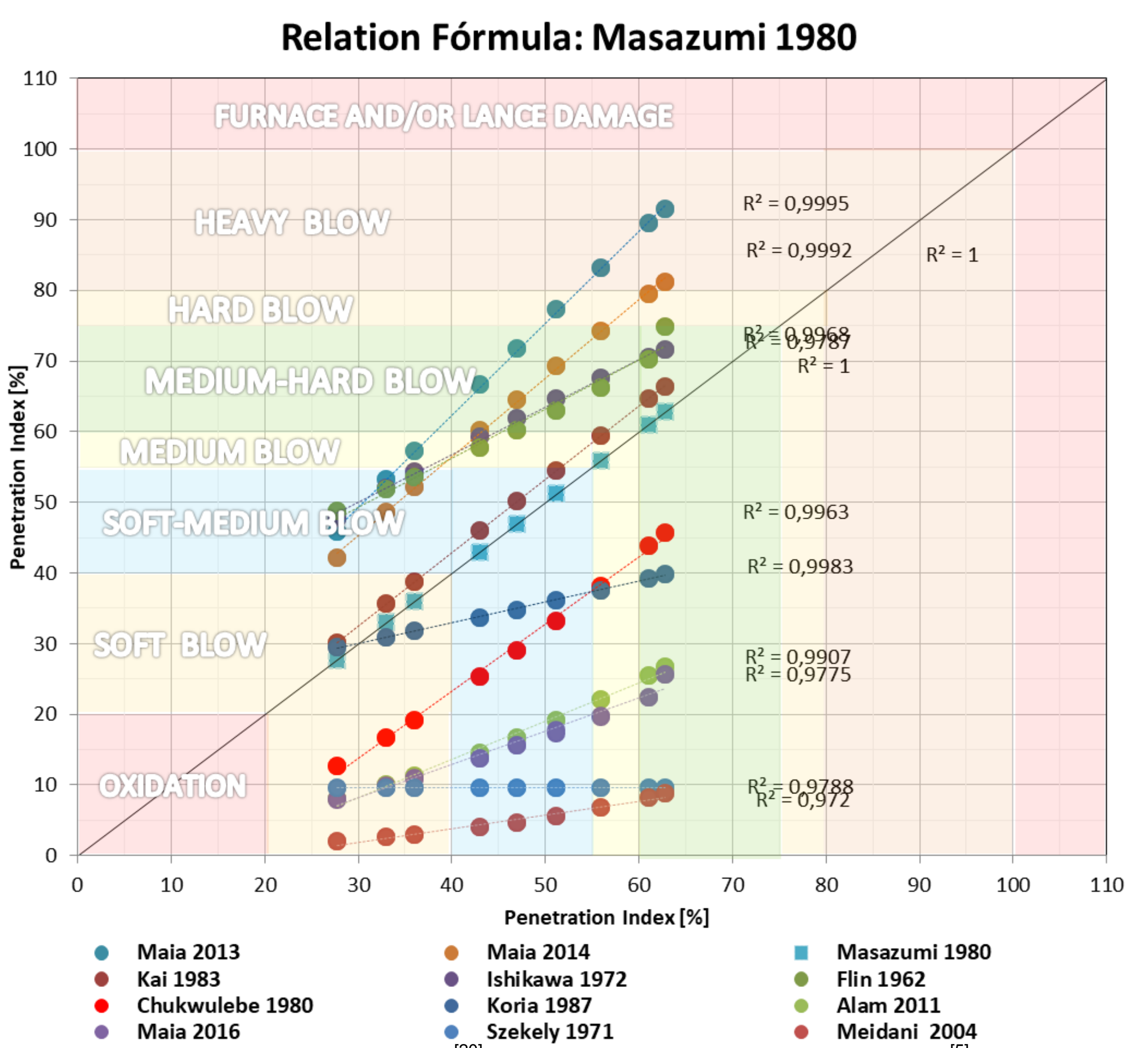


Figure 6 - The penetration index (PI) [20] - the cavity depth divided by Masazumi[5] cavity depth reference.

Figure 6 showed PI using Masazumi[2] reference, equation for penetration index reference, with nozzle factor kn = 1,19 due 05 nozzles lance tip and applied in others equations. Maia[8,9] equations shows high values of penetration in comparison. These equations were obtained from cold models. First one, in 2013, was developed just for top blow. The second equation, in 2014, the bottom blow effects were introduced into momentum equations.

In Maia *et al*[8-10] equations, another factor K was introduced following Meidani *et al*[14] work. The reason for Penetration Index for Maia 2014 to be inferior at Maia 2013 is in the change in the liquid bath promoted for bottom stirring. In this case, bottom stirring interfering in relation L/Lo, increasing Lo and decreasing L. The bottom blow has an effect to change the bath level this mean, changes Lo. Other important consideration, bottom stirring can contribute to reduce bath density, so promote an increase of jet penetration or L. These behaviors changes Penetration Index.

Changes Penetration Index was measured by Maia[10] when static slag layer were study over jet penetration. After consider top and bottom blow parameters, it was added slag layer. In this study was investigated factor k for three phases: metal-gas-slag but without foaming formation. Increasing liquid bath level: metal, bottom bubbling and slag; increases Lo and decreases L. With this work another interpretation can be done about factor K. When the number of process parameters are added into the equation, more phenomenon are represented and there is a tendency to reduce value of factor K.

iii. Koria and Lange Formula Discussion

The figure 7 shown Koria and Lange[7] equation applied.

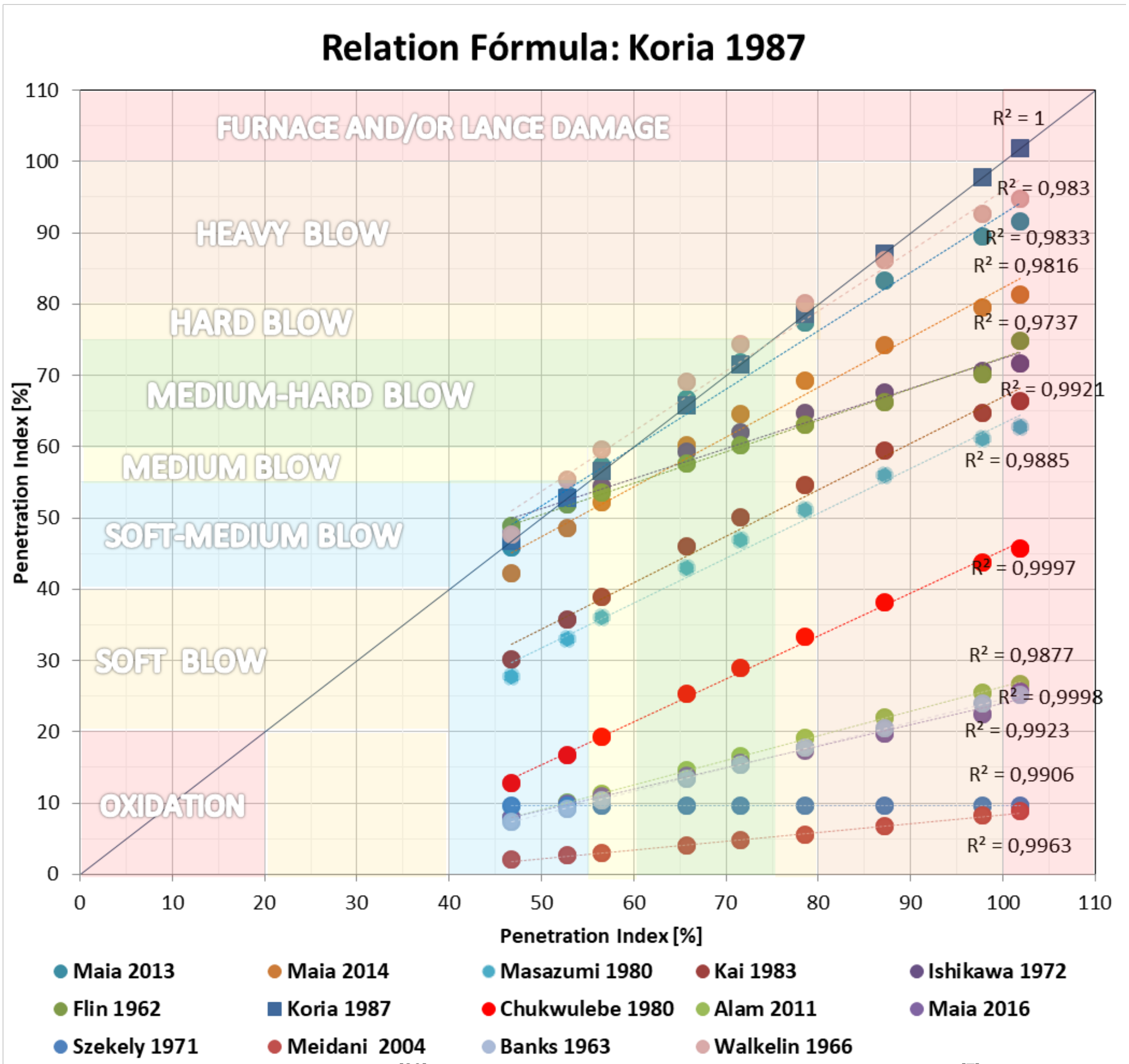


Figure 7 - The penetration index (PI) [20] - the cavity depth divided by Koria and Lange[7] cavity depth.

In general, comparing equations to describe jet penetration, an important parameter is gas velocity. Just Koria and Lange[7] uses reservoir pressure to entrance data to calculate jet penetration. In this study to help comparison the pressure was fixed at 14 bar. In Koria and Lange papers the maximum value informed was 9 bar and in fact informed value for each plant informed was 15 bar. In this figure, were introduced equations from Banks (1963) and Walkelin (1966) *apud* Dogan[19] to show K factor influence. These authors had high K factor values that reduce energy transfer from exit nozzle to the bath surface or in other analyses, K factor is compensation that considering all parameters no described into the equations.

Comparing these equations, it is interesting observe that amount of parameters included into equations changes results interpretation. From heavy/hard blow conditions when penetration happens considering just static bath level to soft blow with bottom strirring and slag layer when compared with traditional static bath level considerations about penetration and her effects during blow.

The entrance BOF blow information like: weights of hot metal and scraps, chemical compositions (in special HM Si), additions (lime, dolomitic lime, coolants and energetics) can be properly converting to equation entrance parameters and by cold models and/or industrial trials determine new factor k for jet penetration.

The next stage will be defined foaming behavior and jet effects. Including new process parameters, it will expect the K factor reduce the value, that will mean well represent blow process.

3 CONCLUSION

Both, the Ishikawa and Segawa[5] formula and the Masazumi[2] formula use nozzle factors to be derived from laboratory experiments. Unfortunately these data were only published for lance angles up to 12°. Today, are common lance angles between 14° - 23° where these nozzle factors are not known. In conclusion there are two options:

1. If one wants to use the formulas the experiments must be repeated and extended for the enlarged blowing angles (university research project), or,
2. Other formulas independent from the nozzle factors must be applied (Kai et al[6], Koria & Lange[7], Maia et al[8-10], Alam et al[13], Meidani et al[14]) The formulas independent from nozzles are able to be included and represent better the blow conditions

For future work, the challenge will be collect these important blow process parameters and with an unique equation able to provide a standard blow profile for all sizes of converter, hot metal variations and additions. In a first stage will be included the concept of Gas Hold Up into bottom stiring conditions and effects of bath level.

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