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Original Article

Evaluation of the permeability of the dripping zone and of flooding phenomena in a blast furnace

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ABSTRACT

In the current scenario of quality impoverishment of the raw materials charged into blast furnaces, it becomes fundamental to understand the phenomena that directly affect the operational stability of these reactors. This paper evaluated a relationship between pressure drop and irrigation density with the intention of associating them to the flooding phenomena that occur in the dripping zone of a coke blast furnace. It was not possible to clearly obtain a relation between the operational instabilities and the occurrence of flooding phenomena, because there is not a clear separation between the days with and without the operational instabilities. However, over a defined range in the diagram, it is noticeable a higher occurrence of instabilities. Analyzing the parameters, the one with greater influence on the permeability of the dripping zone is the size distribution of the coke, evaluated by the calculation of the harmonic diameter.

1. Introduction

1.1. Blast furnace

The blast furnace is a reactor used for the production of hot metal, by the reduction and melting of the metallic burden (iron ore, sinter and pellet) in the presence of a reducing gas generated, mainly, from charcoal, coal or coke. The metallic burden and the coke/charcoal fuels are charged at the top and, on descent, they encounter the counter current reducing gases, obtained by the reaction between the carbon and the oxygen of the air blown by the tuyères, thus obtaining liquid slag and hot metal in the hearth, and dust and gases at the top [1].

The blast furnace is internally divided in zones with different characteristics, containing materials in variable physicochemical states. Fig. 1 schematically shows these regions and their names.

1.2. Dripping zone in a packed bed and the flooding phenomena

The flooding phenomena is defined as the restriction of the liquid flow in a bed of solid particles with countercurrent

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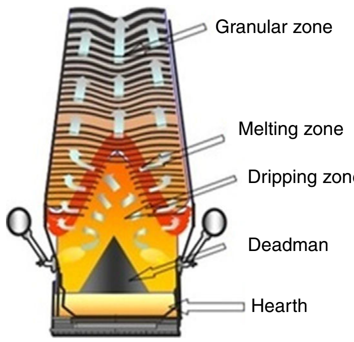

Fig. 1 – Blast furnace divided in zones (Adapted from [2]).

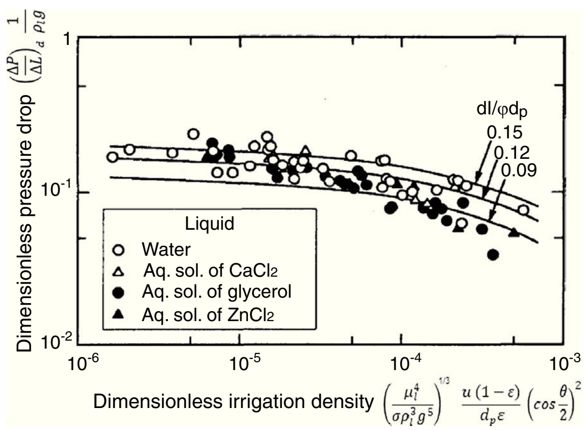

Fig. 2 – Fukutake diagram proposed for different liquids. [4].

gases and liquids. Considering a blast furnace, the liquid stops (retention) and can sometimes rise (reflux), when the gas exerts a limiting force in the opposite direction to the descent of the liquid.

In the dripping zone, there is a downward flow of liquids (hot metal and slag), and an upward gas flow. The permeability depends on the physicochemical quality of the fuel, the liquid flow rate, the slag viscosity and the flow rate of the gases. As coke, liquids and gases need to coexist in the same region, changes in their characteristics or quantities affect the operational stability of the blast furnace. The similarity between this region of the blast furnace and a packed bed with two-phase flow was suggested by some chemical engineers, such as Elliott et al. [3].

Fukutake and Rajakumar [4] performed experiments to analyze the flooding phenomena in the dripping zone. Fig. 2 shows their plotted curves, that describe the limit pressure drop between two points in column until the flooding phenomena occurs, correlated with the characteristics of the packed bed and of the liquid.

The definitions of the variables of this diagram will be presented below.

Matsu-ura and Ohno [5] adjusted the dimensionless irrigation density equation by increasing the dependence on the liquid viscosity. It is important to note that the authors used several gases, liquids and solids for analysis to plot their diagram, but not the materials that are present in a blast furnace.

1.3. Motivation and objectives

It was suggested that the flooding phenomena of the slag in the lower part of a particular blast furnace could be one of the causes of operational instabilities and that these events limit productivity and increase the risk of an operational accident.

The objective of the present work is to evaluate the actual conditions for the occurrence of flooding in a coke blast furnace, with a production capacity of 7500 tons of hot metal per day, associating these phenomena with the operational problems that occurred. Studies of the referenced experimental models were carried out, evaluating the critical variables of the blast furnace operation.

2. Materials and methods

An important part of the work consists of assigning values (operational variables, constants and quality of raw materials from a coke blast furnace) to the equations of both axis of the Matsu-ura and Ohno diagram [5]. The reference curve of $dl/\varphi d_p$ equal to 0.15 mentioned in Fig. 2 was used, and for that the droplet diameter (d_l), shape factor (φ) and coke particle diameter (d_p) of 4.2 mm, 0.70 and 40 mm, respectively.

For practical evaluation of the average coke size at the tuyère level, mechanical devices were developed for extraction and cooling the coke particles.

2.1. Equations and variables of the Matsu-ura and Ohno [5] diagram used for calculations

The equations of the Matsu-ura and Ohno diagram [5], as well as their variables and units used in the calculations, are presented in Eqs. (1) and (2):

Dimensionless pressure drop:

$$\left(\frac{\Delta P}{\Delta L}\right)_d \left(\frac{1}{g\rho_l}\right) \tag{1}$$

ΔP, gas pressure drop between two points (Pa); ΔL, bed length measuring ΔP_d (m); ρ_l, liquid density (kg/m^3); g, acceleration due to gravity (m/s^2).

Dimensionless irrigation density:

$$\left(\frac{\mu^4}{\sigma\rho_l{}^3 g^5}\right)^{1/8} \left(\frac{u_{l(1-\varepsilon)}}{d_p\varepsilon}\right) \left(\cos\frac{\theta}{2}\right)^2 \tag{2}$$

σ, liquid surface tension (N/m); ρ_l, liquid density (kg/m^3). μ, liquid viscosity (Pa s); ε, void fraction (–); d_p, particle harmonic diameter (m); u, superficial liquid velocity based on empty column (m/s); θ, contact angle of liquid on solid (°).

For all variables the liquid considered was the slag. Since the slag has a much higher viscosity and a much lower density than hot metal, flooding will occur first with slag.

2.2. Considerations for dripping zone height and determination of pressure drop

The vertical distance of the packed bed, ΔL, which represents the thickness of the dripping zone in the blast furnace is

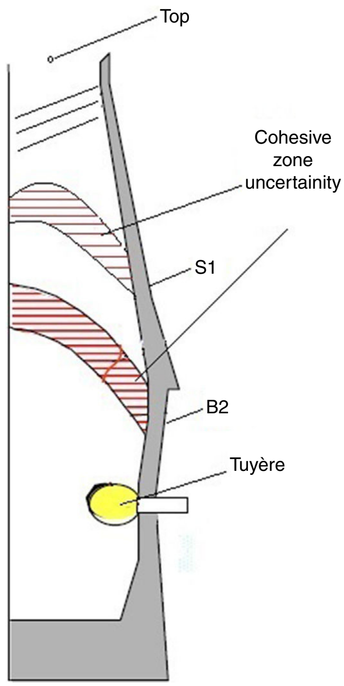

Fig. 3 – Pressure measurements along blast furnace.

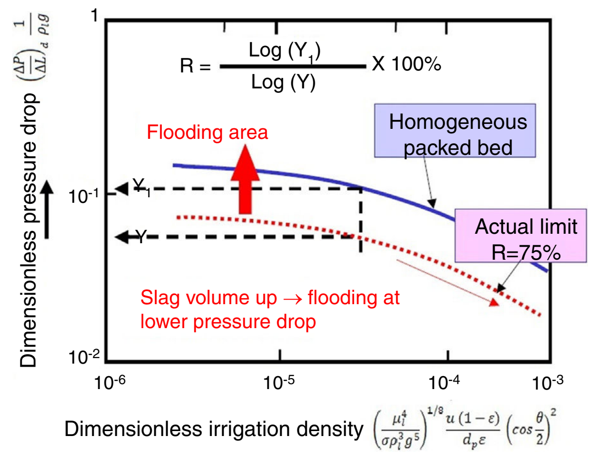

Fig. 4 – Matsu-ura and Ohno [5] diagram adapted by JFE Steel Corporation. JFE Steel Corporation (unpublished).

difficult to define. The lower limit is not the main problem, since the dripping zone is considered where there is coexistence of gas, liquids and coke, and this region can be delimited by the tuyères height. The greatest difficulty is delimiting the upper limit, which would be the boundary with the cohesive zone. Thus, it was evaluated more than one range to define the pressure drop per bed length $\left(\frac{\Delta P}{\Delta L}\right)$.

The following options were considered to evaluate the pressure drop (ΔP),

- Tuyères and 1st level of pressure measurement (B2), $\Delta L = 3.72$ m;
- Tuyères and 2nd level of pressure measurement (S1), $\Delta L = 7.84$ m;
- Tuyères and top pressure (considered as stockline level), $\Delta L = 23.00$ m.

These positions are schematically shown in Fig. 3.

In all cases presented above, the pressure drop that occurs along the tuyère length was considered.

2.3. *Considerations to determine the occurance of flooding phenomena*

JFE Corporation Steel (unpublished work) considered other limits for the occurrence of flooding phenomena in the blast furnace, different from those of Fukutake [4] and Matsu-ura [5]. Fig. 4 presents the results of the JFE study that considers the actual limit for the occurrence of liquid flooding as 75% of the theoretical limit for the blast furnace studied. The justification of these 75% is the difference between experimental model and the industrial scale. Also, JFE specified the harmonic diameter of the coke and the void fraction values.

2.4. *Liquid properties*

The wettability of blast furnace slag in coke was considered null because, according to KANG et al. [6], it is necessary a contact time between slag-coke greater than 60 min to have wettability (angle $\theta < 90°$). Thus, the angle θ considered was 90°.

The density of the slag was considered constant and equal to 2600 kg/ton.

The surface tension was calculated according to MILLS [7] study, considering the sum of the surface tension of each component of slag proportional to its molar fraction.

The viscosity of slag was calculated using the model proposed by Urbain [8], based on temperature and a composition of $CaO–Al_2O_3–SiO_2–FeO–TiO_2–MgO–MnO$.

2.5. *Void fraction of the bed*

The Yagi, Takeda and Omori model [9] was used to determine the void fraction, which is dependent on the harmonic diameter of coke. This model is used internally by the current blast furnace's company. This model is shown in equation:

(3) $\varepsilon = (0.153 * \log d_p) + 0.724$

For the size of the blast furnace that is being studied, it is usually considered a physical degradation of 50% of coke between the charged size and the size in the tuyère level. Coke samples were collected at the tuyère level and this percentage of degradation was determined.

The coke was collected through a shell-shaped device that was inserted into the blast furnace after removal of a tuyère. The coke was packed in a metal box and cooled with nitrogen gas.

The granulometric analysis was done by sieving the coke collected in mesh sieves of 100.0; 75.0; 63.0; 50.0; 37.5; 25.0; 19.0 and 13.2 mm, recording the percentage retained in each mesh.

The harmonic diameter (d_p) was calculated using the formula:

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Table 1 – Characterization of coke samples from the tuyères.

Parameter/sample	Tuyères #18 – aug/16	Tuyères #6 – nov/16	Tuyères #10 – nov/16	Tuyères #27 – feb/17	Average
D_p of coke (m)	0.0541	0.0563	0.0563	0.0503	0.0542
D_p at Tuyères (m)	0.0340	0.0366	0.0249	0.0274	0.0307
Degradation (%)	37	35	56	46	43

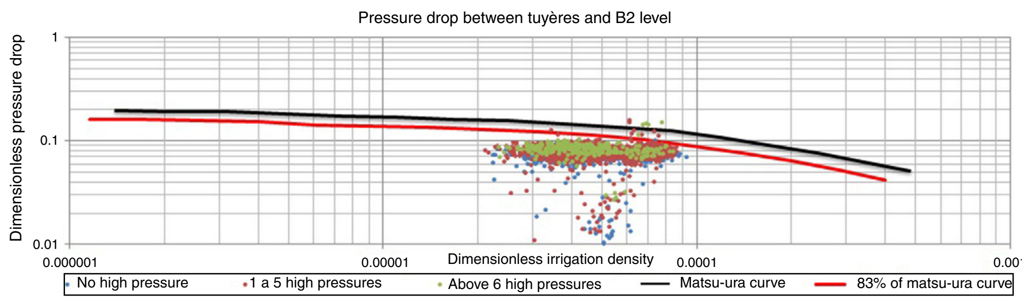

Fig. 5 – Pressure drop between blast and B2 level *versus* irrigation density.

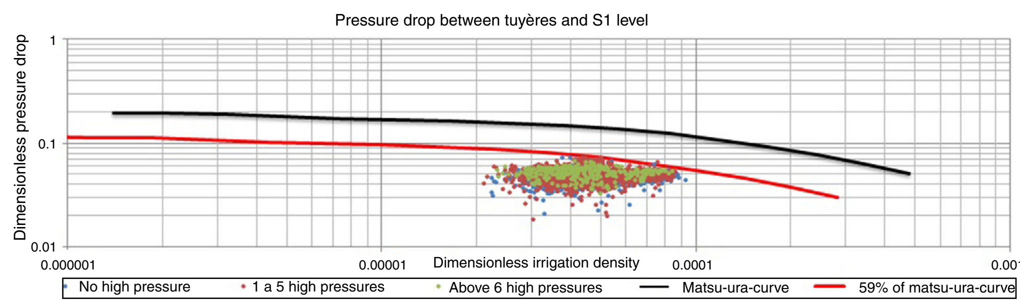

Fig. 6 – Pressure drop between blast and S1 level *versus* irrigation density.

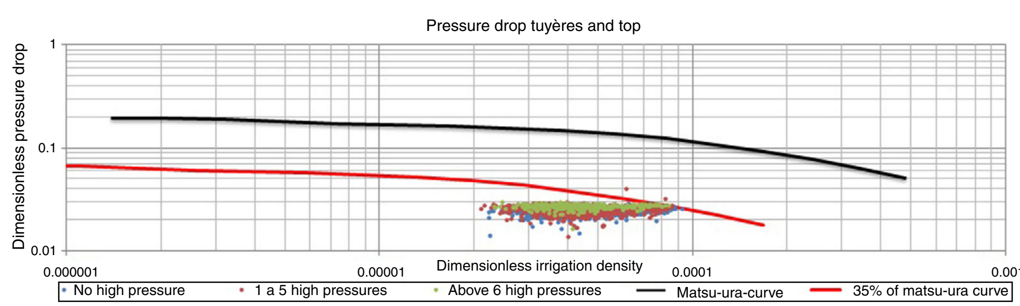

Fig. 7 – Pressure drop between blast and top *versus* irrigation density.

Table 2 – Comparison of flooding real limit for each pressure drop region.

Pressure drop between:	Tuyères and B2 level	Tuyères and S1 level	Tuyères and Top
Flooding real limit comparing to Matsu-ura curve (%)	83	59	35

$$(4)\, d_p = \frac{1}{\sum_{i=n}^{i=1} \frac{(\%i)/100}{d_i}}$$

In which: d_p, particle harmonic diameter (m); n, number of sieves used for screening and where material was retained; (%i), percentage of material retained in the sieve i; d_i, harmonic average diameter of the material retained in the sieve i.

The d_i is calculated by the square root of the product of the apertures of each sieve.

2.6. *Methods for operational instabilities analysis*

The analysis was carried out based on the history of high pressure drop from 2005 to 2015 in the blast furnace. The operational criteria to define high pressure is when the difference between the blow pressure and the top pressure of the blast furnace exceeds 1.75 kgf/cm^2 (0.172 MPa).

The daily instabilities were identified in the flooding diagram and highlighted by frequency of occurrence, so that it

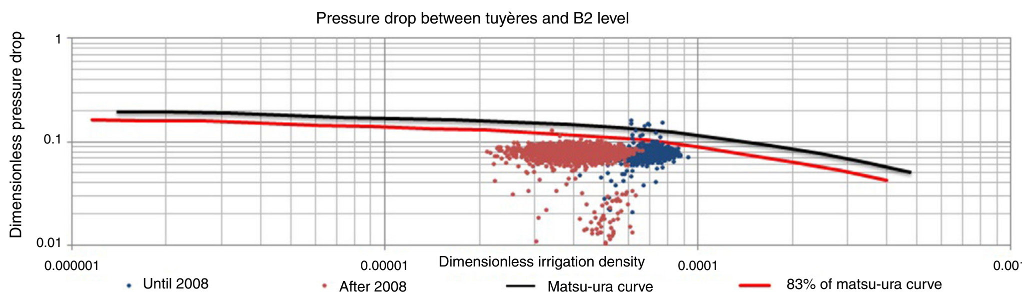

Fig. 8 – Figure 5 without operational instabilities, but separating in two periods, until 2008 and after 2008.

was possible to relate the frequency of instabilities with a region in the graphs.

Critical variables were evaluated between a real data range from 40 mm to 90 mm for coke diameter, from 6.5 kg ton to 8.5 kg ton for hot metal production, from 250 kg/ton to 350 kg/ton for slag rate and from 0.250 to 0.400 Pa s for slag viscosity.

3. Results ans discussion

3.1. *Tuyère coke analysis*

Four coke samples were taken from the tuyères in 2016, one in August, two in November and another in February of 2017. Table 1 shows the coke quality results.

Analyzing the four samples of coke collected from tuyères, it can be observed that samples obtained in November show lower CSR (mechanical resistance of the coke after the reaction with carbon dioxide) and greater degradation of the coke, indicating a size reduction during the process of metallic burden reduction.

The average degradation of the coke at the tuyère level in 2016 and 2017 is approximately 43%.

3.2. *Pressure drop and dripping zone height*

The pressure drop data were plotted in relation to the irrigation density. Fig. 5 shows a closer proximity between the data and the Matsu-ura curve using the pressure drop between the tuyères and region B2 (Fig. 3). This was expected, due to the fact that pressure losses per unit of length in the lower region of the blast furnace are higher because of the proximity to the dripping zone and cohesive zone, in which the permeability is reduced.

As the distance from the dripping zone to the top of the blast furnace increases, the pressure drop per unit length in the bed tends to be lower due to the absence of liquids and molten burden, so the data tend to distance from the curve of Matsu-ura, as observed in Fig. 6.

For the pressure drop between the tuyères and the top of the blast furnace (Fig. 7), the gap between the data and the Matsu-ura curve is even greater. In addition, the data are more concentrated and present a flat top limitation. This limitation may be related to the operating procedure to reduce blast flow rate (consequently reducing liquid production) when the pressure difference between the top and the blast exceeds 1.75 kgf/cm^2 (0.172 MPa).

Table 3 – Impact of coke harmonic diameter in irrigation density.

Variables	Blast furnace 1
Dimensionless irrigation density (MATSU-URA)	1.00E−06
Production (ton/day)	1.36E+02
Slag-rate (kg/ton)	2.51E+01
Slag viscosity URBAIN MODEL (Pa.s)	1.27E−02
Harmonic coke diameter at Tuyères (m)	−6.20E−04
Harmonic coke diameter at coke oven (m)	−1.02E−03
Void fraction (–)	−2.82E−04
Surface tension (N/m)	−1.29E−11

Table 2 summarizes the real limits for flooding for each pressure drop region. The pressure drop between tuyères and B2 level is the closest value from Matsu-ura curve (83%) and is the blast furnace region that is more likely of dripping zone limit.

3.3. *Comparison between before and after the Year of 2008*

Fig. 8 shows the points of Fig. 5 without operational instabilities, but separating in two periods, until 2008 and after 2008. Mainly, the points that exceed 80% of the flooding curve happened before 2008, when coke harmonic diameter was smaller.

3.4. *Sensitivity analysis of irrigation density and its critical variables*

Table 3 quantifies some impacts of the critical variables in the Matsu-ura irrigation density variation. According to sensitivity analysis, for each 1.00×10^{-6} of irrigation density the impact of decreasing 1.92 mm in coke size at Coke Oven is equivalent to increase 25.1 kg/ton of slag rate, or 136 ton/day of hot metal production or 1.27×10^{-2} poise of slag viscosity.

Separating coke particles diameter in three periods, from 2005 to 2008, from 2009 to 2011 and from 2012 to 2015, the coke size increased about 10 mm in the period. This raise may enable the increase of the other critical variables maintaining the same irrigation density.

4. Conclusion

1) Pressure drop between the blast and the level B2 was adequate to evaluate discrepancies in the intensity of irrigation. However, it is not possible to determine an explicit limit for flooding occurrence, since the separation between the days with and without operational instabilities, it is not clear. Above 83% of the MATSU-URA curve, there is always the occurrence of high pressures.
2) The current harmonic diameter of the charged coke, around 65 mm, would hardly bring flooding problems in the dripping zone, considering the current and past levels of hot metal production (from 6.5 to 8.5 kg/t/day), slag rate (from 250 to 350 kg/t) and slag viscosity (from 0.250 to 0.450 Pa s). However, external factors such as blast furnace drainage and the physical and chemical quality of coke and metallic burden are important.

Conflicts of interest

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The authors declare no conflicts of interest.

REFERENCES

[1] Machado MLP, Sobrinho VPFM, Arrivabene LF. Siderurgia Para Não Siderurgistas. Associação Brasileira de Metalurgia, Materiais e Mineração – ABM; 2003.
[2] Araújo LA. Manual de Siderurgia. 2nd ed. São Paulo: Editora Arte & Ciência; 1997.
[3] Elliott JF, Buchanan RA, Wagstaff JB. Physical conditions in the combustion and smelting zones of a blast furnace. J Metals 1952;4.
[4] Fukutake T, Rajakumar V. Liquid holdup and abnormal flow phenomena in packed beds under conditions simulating the flow in the dropping zone of a blast furnace. ISIJ International; 1982. p. 355–64.
[5] Matsu-ura M, Ohno Y. Modelling of gas and liquid flow in two dimensional packed bed and analysis of dropping zone in blast furnace. ISIJ International; 1994. p. 15–9.
[6] Kang TW, Gupta S, Saha-Chaudhury N, Sahajwalla V. Wetting and interfacial reaction investigations of coke/slag systems and associated liquid permeability of blast furnaces. ISIJ International; 2005. p. 1526–35.
[7] Mills K. The estimation of slag proprieties. Southern African: Southern African Pyrometallurgy; 2011.
[8] Urbain. Viscosity estimation of slag. Steel Research; 1987. p. 111–6.
[9] Yagi J, Takeda K, Omori Y. Two-dimensional simulation on the gas flow and heat transfer in the blast furnace. Transactions ISIJ; 1982. p. 884–92.

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