Burden Distribution Analysis by Digital Image Processing in a Scale Model of a Blast Furnace Shaft

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During the realigning of Aceralia’s blast furnace B in Gijón, a 1/10 scale half-section, three-dimensional cold model of the BF shaft was built to test charging patterns and the effect of gas flow in burden distribution. The front side of this half model is closed by a methacrylate sheet that allows images of the burden distribution inside the model to be obtained, during and after the charging process. Image processing techniques were applied to obtain useful information from burden profile images. A complete study of a charging pattern is presented in this paper.

The model has allowed study of some local effects of gas flow in burden distribution, such as changes in the final coke layer during ore charging, and the formation of a narrow window in the centre of the model that connects the successive coke layers.

KEY WORDS: ironmaking; blast furnace; cold model; burden distribution; gas flow.

1. Introduction

Burden plays a key role in blast furnace performance. This is the reason why such a large number of studies concerning the influence of burden properties and burden distribution in the blast furnace have been performed in the past years, and are continuing.1–4)

The development of reduce and real scale models that allow to see how the burden should behave inside the blast furnace, are an important part of these studies.5–7) These models try to reproduce main features of the blast furnace and show themselves as an useful tool to elucidate the best ways to distribute the burden. After testing a charging method in the model, this may be applied in the real blast furnace knowing its behaviour beforehand.

Digital Image Processing has a broad spectrum of applications in many different fields: interpretation of images acquired by satellites, medical diagnosis from radiology, and automatic inspection in industry are some examples.8) In this way, digital image processing may be used not only to enhance the quality of the images obtained by an optical device but also to work out useful information from them in an easier and more accurate way than human inspection.

In the present work, a 1/10 scale cold model of Aceralia’s blast furnace B shaft and Bell-less top charging system has been developed. A complete sequence of the charging process for coke and ore has been recorded, employing a charge-coupled device (CCD) camera to take images of burden profile evolution during the trial. The images obtained from the model were subsequently processed in a computer to study the evolution of burden distribution during the charging process.

The goal was twofold: to develop a tool that could be used for routine test of blast furnace charging patterns, and to study a particular charging pattern employed currently in Aceralia’s blast furnaces for normal operation.

2. Experimental Method and Tools for Analysis

Figure 1 shows a survey of the 1/10 blast furnace shaft model. It reproduces a semicircle section of the blast furnace, it is closed by a methacrylate sheet for its front side and it is endowed with a set of ten equidistant taps. Through these taps a hollow wire with a needle-shaped end can be introduced in the shaft model to obtain pressure drops measurements inside of burden. Figure 2 shows the inlet air system and the experimental device to measure the pressure drops.

On top of the shaft model a charging device resembling a Paul–Wurth system is located (Fig. 3). It is provided with a small hopper closed by a valve to control of flow of materials. A chute with regulating tilt angle and being able to rotate around the centre of the model is employed to distribute the material.

Tables 1 and 2 reproduce the charging pattern employed in Aceralia (r) and the scaled charging pattern for the model (m). Ore is composed by a mixture of pellets, sinter and flux. This last was not included in the charging pattern for the model, so the ore for the model was composed by a mixture of 60% pellets and 40% sinter. One original feature of this charging pattern is the way in which the blast furnace is charged, beginning at the centre of the blast furnace and finishing at the wall.

To accomplish the necessary size reduction for material charged in the model ore and coke small particle fractions was sieved and mixed again to reproduce a scale size distri-
bution resembling that employed in the real plant. Pellets, scaled also to a proper reduced size, were made employing a mixture of magnetite, concrete and titanium dioxide. This last one as a pigment to obtain an almost white coloration that allows to distinguish among coke and ore layers.

Tables 3, 4 and 5 show a comparison among relevant physical properties of burden materials for the actual blast furnace and the model.

The air flow through the model was calculated to obtain a Froude number \( F_r \) equal to the Froude number for gas flow in the throat of the actual blast furnace shaft.\(^9\)

\[
F_r = \frac{\rho_R \cdot u^2}{(\rho_R - \rho_g) \cdot g \cdot L} \quad \quad \quad (1)
\]

As far as the known magnitude is the total gas flow in the blast furnace throat rather than the gas velocity, it is convenient to rewrite Eq. (1) as a function of that. Equalling Froude numbers for the blast furnace and the model and after same mathematical manipulation the relationship between the gas flow for the model and the gas flow for the

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**Fig. 1.** A 1/10 scale model of the blast furnace shaft (measures in cm). (T) Top view. (F) Front View (L) Lateral view.

**Fig. 2.** Inlet air system and pressure drops measuring system.

**Fig. 3.** Charging device system for the model (measures in cm).

**Table 1.** Charging pattern for coke. [r] Actual blast furnace. [m] scaled model employed in this study.

| Angle (°) | 2 | 12 | 22 | 28 | 32 | 35 | 38 | 41 | 44 | 47 | 50 |
|-----------|---|----|----|----|----|----|----|----|----|----|----|
| Weight (kg) | r | 2714 | 2443 | 2036 | 1080 | 1000 | 2307 | 2130 | 2483 | 2483 | 2714 |
|           | m | 1,420 | 1,290 | 1,080 | 1,000 | 1,000 | 1,230 | 1,210 | 1,290 | 1,290 | 1,420 |
| Cumulated Weight (kg) | r | 2,714 | 5,157 | 7,193 | 9,093 | 11,400 | 13,841 | 15,280 | 16,286 | 16,286 | 19,000 |
|           | m | 2,140 | 3,710 | 5,790 | 7,690 | 9,600 | 11,240 | 12,790 | 12,790 | 12,790 | 14,400 |

**Table 2.** Charging pattern for ore. [r] Actual blast furnace. [m] Scaled model employed in this study.

| Angle (°) | 2 | 12 | 22 | 28 | 32 | 35 | 38 | 41 | 44 | 47 | 50 |
|-----------|---|----|----|----|----|----|----|----|----|----|----|
| Weight (kg) | r | 12220 | 12200 | 12200 | 12200 | 12200 | 12200 | 14064 | 15759 | 16098 |
|           | m | 6,321 | 6,321 | 6,321 | 6,321 | 6,321 | 6,321 | 7,310 | 8,170 | 8,342 |
| Cumulated Weight (kg) | r | 12220 | 24460 | 36979 | 51003 | 67606 | 67606 | 82860 | 96580 | 102800 |
|           | m | 6,321 | 12,642 | 19,178 | 26,488 | 26,488 | 26,488 | 34,658 | 43,000 |
| Weight Pellets (kg) | r | 7,320 | 7,320 | 7,320 | 7,320 | 7,320 | 7,320 | 8438 | 9455 | 9659 |
|           | m | 3,793 | 3,793 | 3,793 | 3,793 | 3,793 | 3,793 | 4,386 | 4,902 | 5,005 |
| Weight Sinter (kg) | r | 4,880 | 4,880 | 4,880 | 4,880 | 4,880 | 4,880 | 5,016 | 5,626 | 6,034 |
|           | m | 2,528 | 2,528 | 2,528 | 2,528 | 2,528 | 2,528 | 2,615 | 2,924 | 3,268 |
blast furnace can be expressed as\(^{(2)}\):

$$Q^m = \left( \frac{\rho_g}{\rho_p} \right)^m \left( \frac{L_p}{L} \right)^5 \cdot Q$$

Where \(\rho\) represents density, \(L\) the representative length, the superscript \(m\) refers to the model and the subscripts \(g\) and \(p\) refer to gas and solid, respectively. Table 6 shows a comparison among actual and reduced magnitudes, concerning the gas flow.

### Table 3. Comparison between physical properties of coke employed in the actual blast furnace and coke employed in the scaled model of this study.

| Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|----------|--------------|------------------|-------------|---------------|--------------|
| 3.41%    | 30±3°        | 0.99 kg/L         | 0.512 kg/L  | 48.1%         | 0.73         |
| 1.01%    | 28±5°        | 65.02%            | 7.48%       | 50.16         | 91.54%       |

**Table 4.** Comparison between physical properties of sinter employed in the actual blast furnace and sinter employed in the scaled model of this study.

| Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|----------|--------------|------------------|-------------|---------------|--------------|
| 0.14%    | 30±3°        | 1.13 kg/L         | 1.35 kg/L   | 53.1%         | 0.44         |
| 1.2%     | 30±5°        | 50±10            | 7±10        | 19±2          | 9.68%        |

**Table 5.** Comparison between physical properties of pellets employed in the actual blast furnace and pellets employed in the scaled model of this study.

| Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|----------|--------------|------------------|-------------|---------------|--------------|
| 1.49%    | 27±3°        | 3.69 kg/L         | 2.36 kg/L   | 36.04%        | 0.99         |
| 1.9%     | 0.9%         | 60.6%             | 34.0%       | 22.1%         | 12.7         |

**Table 6.** Relationship among gas flow condition for the actual blast furnace and the scaled model.

| Magnitude  | Actual | Scale factor | Model |
|------------|--------|--------------|-------|
| \(L_m\) (m) | 1      | 1/10         | 1/10  |
| throat gas | 2      | 403          | Air   |
| gas Pressure (atm) | 20.4 CO | 23.7 CO\(_2\) | 3.0 H\(_2\) | 52.9 N\(_2\) |
| Temperature (°C) | \(\rho_g\) (g/L) | 1.88     | 1.168 |
| Chemical composition (Vol%) | 1.09 | 1.09 |
| Froude number | \(Q\) (m\(^3\)/s) | 270000   | 611   |

The model was filled with layers of coke and ore until reaching a height nearly below the stock level, keeping room enough to charge the last two layers of coke and ore employing the chute. After this, the air supply was plugged in to begin the trial. Coke and ore were charged ring by ring taking pictures with the CCD camera of the layer profile after each dump. The images were stored in a hard disk in standard ‘bmp’ format.

**Figure 4** shows an example of these images after discharging the first and second ring of coke. Quantitative information may be obtained from the images: first, an interest area is selected, containing the profile modified after the last dump. Then, this new image is processed to obtain the boundaries of the layer.

Unfortunately, it is not possible to obtain a clean image of the layer boundary just employing standard edge detectors. The reason is that edge detection from a digital image is mainly based on the analysis of local changes in pixel intensity or colour.\(^{8}\) As far as the images reproduce the burden granular structure there is not a simple way to distinguish the edges for individual coke and ore particles focusing only on the frontier of the total layer.

For this reason, it was necessary to develop a special algorithm that would work with the number of pixels of each colour (histogram) associated with the image and their spatial distribution. So, a binary mask is created that encloses the whole layer. After applying it to the original image, the histogram is calculated and a threshold is defined. Pixels whose abundance, according to the histogram, is less than the threshold are turned to black; otherwise they are turned to white. Trying different thresholds, it is possible to eventually obtain a black and white image with a well defined boundary for the layer. This b/w image is improved em-
ploying a morphological filter to perform binary closure (Insulated white pixels surrounded by black ones are turned to black, and vice versa).

Applying a standard edge-detection technique to this new image, the boundary of the layer is worked out. The image of the boundary is scaled from pixels to centimetres, and the final result is ready for thickness and slope angles to be extracted, and also to compare the evolution of the layer as new material drops inside the model.

The whole process described above is shown step by step in Figs. 5(A) to 5(D) for the coke layer after dumping the second coke ring.

3. Experimental Results and Discussion

Figures 6 and 7 show the images of the coke layer after dumping ring no. 2 and ring no. 9, the first and last coke rings respectively, and the result obtained after applying the technique described above for edge detection. These figures
have been scaled from pixels to centimetres. The origin of co-ordinates has been located in the centre of the model for the horizontal axis, and at the lower end of the model throat for the vertical axis. The axis of symmetry of the rings is shifted about one cm to the left of the centre of the model, probably due to shortcomings of the charging system.

Figures 8 and 9 show the images of ore layers in the same way that in the coke case.

Figure 10 shows all the coke profiles obtained put together; the evolution of coke burden distribution during the charging process can be seen.

There are several interesting features regarding this last figure. First, the lower limit of the coke layer remains almost unchanged during the whole process and fits among the several profiles. This exemplifies the validity of the method employed. Second, in general, the layer is stable. Each new dump tends to complete the previous one that remains almost unaltered. This is due to the charging method that locates the first ring in the centre of the blast furnace in a highly stable position. Third, there is a slight increase of the layer thickness in the centre. Gas flow becomes more and more central as new coke rings are added near the wall, generating a lifting force that tends to loosen the coke and expand the bed in the centre.

The ore profiles obtained have been put together in Fig. 11 in order to be compared. In this case, each new ring added to the ore layer covers all the previous ones. The structure of the layers seems largely altered at the centre of the blast furnace model where coke and ore are mixed. In fact, during the trials, after dumping the first ore ring, the central part of the coke burden that remained uncovered began to fluidize. Fine coke particles move out of the bed, dragged by the gas, and fall again on the bed surface. This phenomena suggests a local deflection of the gas flow due
to the decrease of permeability in the zone covered by the new ore ring. When new ore rings are added, ore and coke tend to mix at the centre, and ore never covers completely the coke layer.

Some calculations, only partially published, obtained from a mathematical model for burden and gas distribution, appear to confirm these results. Gas velocity at the surface of the burden has been calculated solving Ergun’s equation by numerical methods. The minimum fluidization velocity can be calculated equalling the drag force of the gas to the weight of the burden particles:

\[ U_{mf} = \frac{3.5 \rho_s}{\phi \rho_m d_p} \]

and following the approach of Wen and Yu

\[ \frac{1 - \varepsilon_{mf}}{\phi^2 \varepsilon_{mf}} = 11 \]

\[ \frac{1}{\phi^2 \varepsilon_{mf}} = 14 \]

Equation (3) can be expressed as:

\[ U_{mf} = \frac{-1650 \frac{\mu}{d_p} + \left( 1650 \frac{\mu}{d_p} \right)^2}{49 \frac{\rho_p}{d_p}} \]

Where \( \rho_s \) and \( \mu \) represent density and viscosity of gas, respectively, \( \rho_p \) and \( d_p \) the bulk density and diameter of coke particles, and \( g \) the gravitational constant.

**Figure 12** shows both the theoretical minimum fluidization mass velocity \( (G_{mf} = \rho_s U_{mf}) \) and the result for mass velocity of gas \( (G = \rho_s U) \) at the surface of the burden after dumping the first ore ring (Fig. 8). The later was obtained from the aforementioned gas model. As can be seen, gas velocity decreases strongly in the area covered by the ore ring (10 to 30 cm from the centre of the model). Focusing in the central area of the model, the gas velocity reaches the value of minimum fluidization velocity for coke particles with a diameter of about 2.2 mm, this value decrease toward the wall of the model. At a distance around 10 cm from the centre of the model, where the beginning of the ore ring is located, only those coke particles with a diameter less or equal to 0.9 mm would be dragged by the gas.

These result are in agreement with the observed movements of fine coke particles at the centre of the model described above. It is the aim of the authors to present a full discussion of results from both models in a future publication.

**Figure 13** shows a comparison between the coke profile before and after charging the first ore ring. A slight collapse of the coke layer can be observed. The thickness of the coke layer has increased about 1 cm from the centre to a distance of 13 cm, and has decreased about 0.5 cm from there to the wall. This collapse takes place during the first ore ring dump; the coke layer is on an unstable equilibrium mainly due to the low cohesion of the slope base, located at the centre of the model. The force supplied by the falling ore, plus the added weight, makes the coke layer slip until a new stable slope is reached.

There is no further collapse after the first ore ring is loaded. **Figure 14** shows a comparison between coke layers after dump of the first ore ring and after dump of the ninth one. Both profiles are almost identical except for the centre of the model, where coke has been rising as new rings of ore are added, burying completely the tip of the ore layer. As a result, a circular window of coke almost 2 cm. in diameter remains in the centre of the model, connecting one layer of coke with the next one when the charging process
The charging pattern was designed to obtain a greater coke thickness in the centre of the blast furnace and near the wall in order to assure central gas flow and prevent scaffolding in the walls. The formation of such a coke window, as has been described above, was an unexpected effect that led not only to a better understanding of the burden distribution but also to considering the possibility of using it to improve gas efficiency. Thus the question is whether or not it would be possible to modify the position and weight of the first ore ring to generate a wider or narrower coke window, acting like a diaphragm to produce a more central or more peripheral gas flow depending on the process necessities.

4. Conclusions

Using a half-section, three-dimensional model of a blast furnace shaft, and also digital image acquisition and process techniques, a complete charging process experiment was performed. The following results may be highlighted:

(1) Accurate information of the burden distribution and evolution of coke can be obtained by rebuilding the layer profiles, using the layer images. It is a useful tool for this kind of analysis that may be employed to study any burden distribution.

(2) Gas flow effect must be taken into account in charging patterns definitions because it can strongly alter the burden distribution. This does not make it into a nuisance, it may be employed to improve the burden conditions.

(3) As new rings are added at charging time, they modify the local gas flow, which drags coke particles, affecting the final shape and position of the coke layer.

(4) For the case studied in this work, the formation of a narrow window in the centre of the model, connecting the successive coke layers, is a consequence of the previous conclusion.

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