1. Introduction

During the past three decades a lot of effort has been made to estimate gas flow and gas distribution inside the blast furnace. There is a sound conviction that the understanding of gas behaviour in the blast furnace is the key to improving blast furnace performance.

Many physical and mathematical models have been developed in order to estimate the mutual influences between burden and gas distributions. Sometimes these models were developed specifically to study this problem and in more recent times they were part of global blast furnace formulations. Ergun's equation or expressions derived from it have been widely employed to estimate gas flow through porous media in general and through the blast furnace shaft and throat as a particular application. The Ergun approach to gas flow through packed beds has the advantage that it relies only on gas and packed bed properties that can be easily estimated.

In a previous paper, some results obtained from a 1/10 scaled model of Aceralia's blast furnace B shaft were presented. In that work, image processing techniques were applied to obtain information from burden profile images. Tables 1 to 4 show the relevant features of this model and more details can be found in the mentioned paper. The model allowed for the study of some local gas flow effects on burden distribution, such as changes in the final coke layer during ore charging at its top, and the formation of a narrow window in the center of the model that connects successive coke layers. In particular, fluidisation of the central part of the coke burden was observed after dumping the first ore ring. Local gas flow deflection, due to the decrease of permeability in the zone covered by the new ore ring was suggested as a reason to explain this phenomenon.

In this work, the existence of such local deflexion of the gas flow is estimated by means of a combination of two models; the first one is a model to estimate the burden distribution in the blast furnace shaft, departing from the charging patterns used to load it. This model was employed to characterize the packed bed medium that constitutes the blast furnace burden, delimiting areas of coke and ore. The second model is a dynamic modelling of the gas mass velocity that was developed departing from Ergun's equation.

2. Burden Distribution Model

A brief description of the burden distribution model is included here to clarify its basic features. A more detailed description has been published elsewhere and it will not be repeated here.

The model was initially developed to study Aceralia's blast furnace B throat and shaft burden distribution. The charging system is a Paul Wurth bell-less top, so, ore and coke tend to accumulate inside the blast furnace in the shape of concentric rings of material.

The model takes charging patterns established by blast furnace operators as inputs. Every pattern is defined by a set of tilt angles for the charging system chute and the ore and coke weights discharged at each angle.

The charging pattern is employed by the model to estimate the shape of the various rings formed inside the blast furnace after every material discharge. To perform these calculations, the contact point between the ore or coke stream coming down from the end of the chute and the burden surface is estimated first. Once this point has been
obtained, a pair of second degree polynomials is calculated to describe the shape of the ring. Both of them have a maximum located at the contact point and are symmetrical with respect to this point, the first derivative at their turning point fits the tangent of the repose angle of the discharged material, and the revolution volume between them and the previous burden surface should fit the volume of discharged material.

Successive rings define the layers of ore and coke. An example can be found in Fig. 1 showing the results obtained from this model for the charging pattern described in Tables 5 [r] and 6 [r].

The descent of the burden along the blast furnace shaft was simulated employing a plug flow model. 13) This allows

### Table 1. Comparison between physical properties of coke employed in the actual blast furnace and coke employed in the scaled model of this study.

| COKE (actual) | Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|---------------|----------|--------------|------------------|-------------|---------------|--------------|
| 3.41%         | 34°±3°   | 0.99 kg/l    | 0.513 kg/l       | 48.1%       | 0.72          |
| SIZE DISTRIBUTION (mm) | d<20 | 20<d<40 | 40<d<70 | 70<d<100 | 100<d | Mean size | 20<d<70 |
| 1.01%         | 26.52%   | 65.02%       | 7.46%            | -           | 50.16         | 91.54%       |

| COKE (model) | Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|--------------|----------|--------------|------------------|-------------|---------------|--------------|
| 3.41%        | 34°±3°   | 1.26 kg/l    | 0.55 kg/l        | 56.3%       | 0.86          |
| SIZE DISTRIBUTION (mm) | d<2 | 2<d<4 | 4<d<7 | 7<d<10 | 10<d | Mean size | 2<d<7 |
| 1.01%        | 26.52%   | 65.02%       | 7.46%            | -           | 5.01          | 91.54%       |

### Table 2. Comparison between physical properties of sinter employed in the actual blast furnace and sinter employed in the scaled model of this study.

| SINTER (actual) | Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|-----------------|----------|--------------|------------------|-------------|---------------|--------------|
| 0.14%           | 30°±3°   | 3.95 kg/l    | 1.49 kg/l        | 49.6%       | 0.54          |
| SIZE DISTRIBUTION (mm) | d<0.5 | 0.5<d<1 | 1<d<2 | 2<d<3 | 3<d<5 | 5<d | Mean size | 0.5<d<5 |
| 1.2%           | 25.1%    | 41.6%        | 17.5%            | 11.6%       | 3.1%          | 95.8%        |

| SINTER (model) | Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|----------------|----------|--------------|------------------|-------------|---------------|--------------|
| 0.14%          | 30°±3°   | 3.95 kg/l    | 1.49 kg/l        | 49.6%       | 0.54          |
| SIZE DISTRIBUTION (mm) | d<0.5 | 0.5<d<1 | 1<d<2 | 2<d<3 | 3<d<5 | 5<d | Mean size | 0.5<d<5 |
| 1.2%          | 25.1%    | 41.6%        | 17.5%            | 11.6%       | 3.1%          | 95.8%        |

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

| PELLETS (actual) | Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|------------------|----------|--------------|------------------|-------------|---------------|--------------|
| 1.49%            | 27°±3°   | 2.36 kg/l    | 1.49 kg/l        | 36.04%      | 0.99          |
| SIZE DISTRIBUTION (mm) | d<0.5 | 0.5<d<1 | 1<d<1.4 | 1.4<d<1.8 | 1.8<d | Mean size | 0.8<d<1 |
| 1.3%            | 1.9%     | 60.6%        | 34.0%            | 2.2%        | 12.7          | 94.6%        |

| PELLETS (model) | Humidity | Repose angle | Apparent density | Bed density | Void fraction | Shape factor |
|-----------------|----------|--------------|------------------|-------------|---------------|--------------|
| 1.49%           | 27°±3°   | 2.36 kg/l    | 1.49 kg/l        | 36.04%      | 0.99          |
| SIZE DISTRIBUTION (mm) | d<0.5 | 0.5<d<1 | 1<d<1.4 | 1.4<d<1.8 | 1.8<d | Mean size | 0.8<d<1 |
| 1.3%           | 1.9%     | 73.6%        | 23.6%            | 1.64%       | 1.2           | 97.3%        |

### Table 4. Relationship among gas flow condition for the actual blast furnace and the scaled model.

| Magnitude | Actual | Scale factor | Model |
|-----------|--------|--------------|-------|
| L (m)     | 1      | 1/10         | 0.1   |
| throat gas Pressure(atm) | 2      | 40          | Air 1 |
| Temperature(°R) | 20.4 CO | 23.7 CO2 | 21 O2 | 99 N2 |
| Chemical composition (%vol.) | 3.0 H2 | 22.9 N2 | 79 N2 |
| pL(gr/l)  | 1.88   | 1.168        | 1.09  |
| Froude number | 1.09  | 1.09         |       |
| Q(m3/SPT/b) | 27000 | 1.2Ã·(pL/p0)·(1/2[y·(L2/L2)]) | 611   |
the estimation of the burden layer after simulating its loading. The main features which taken into account by the descent model are the slope decrease and the progressive thickening of burden layers as they descend through the shaft.

A version of the model just described is at present used in Aceralia to estimate the burden distribution inside the shafts of blast furnaces A and B on-line.

A special version was developed to estimate the burden distribution in the 1/10 scale shaft model mentioned above. Tables 5 and 6 reproduce the charging pattern used at Aceralia (r) and the scaled charging pattern for the model (m).

By means of image acquisition and image processing techniques, it was possible to obtain the ring profiles once loaded into the physical scaled model. Coke and ore were charged ring by ring taking pictures with a CCD camera of the layer profile after each dump. The images were stored in a hard disk in standard ‘bmp’ format. 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 layers. (A complete description of this technique can be found in Ref. 10). These profiles can be compared with the results for the burden distribution model by simply superimposing them. An example of this is shown in Fig. 2, for the case of coke ring n°2. Numerical results are in good agreement with the profiles obtained from the scale model only for the case in which air is not supplied to it to simulate the gas flow. Otherwise, it is necessary to modify the slope angles for ore and coke layers that no longer coincide with the repose angle of these materials. As will be shown later, other phenomena cannot be simulated with this burden distribution model.
3. Mathematical Gas Flow Model

The model is based on the differential form of the aforementioned Ergun equation:

\[-\nabla P = \frac{\dot{G}}{\rho_g} (f_1 + f_2) \] ..........................(1)

where:

\[ f_1 = \frac{(1 - e)^2 \mu_g}{d^2 e^2 \rho_g} \] ..........................(2)

\[ f_2 = 1.75 \frac{(1 - e)}{d e \rho_g} \] ..........................(3)

In order to complete this equation, it is necessary to add an adequate continuity equation.

\[ \nabla \cdot \dot{G} = 0 \] ..........................(4)

Where the existence of sources has not been consider.

Equations (1) to (4), together with the appropriate boundary conditions complete the statement of the problem. For the particular case of the previously mentioned physical model, these boundary conditions can be specified as follows: There is no pressure distribution along the top surface of the burden; pressure is equal to atmospheric pressure along the burden surface. Gas velocity through this surface is considered perpendicular to it. The wall of the model is considered impervious so gas velocity is thus parallel to the wall near to it. The center axis is considered as a symmetry axis. The lower part of the physical model is closed with a conical metallic grid. An isobaric boundary condition was imposed at this surface. Air is supplied to the model through this metallic grid and can recirculate freely in the area of the model located below the conical metallic grid. It is therefore expected that this recirculation compensates any pressure gradient before it enters into the burden region.

According to the cylindrical symmetry prescribed for the model, Eqs. (1)–(4) were solved on the z–r plane. These equations were rewritten into a finite-difference representation employing a grid of 150 radial and 210 axial divisions and were numerically solved via the use of the successive over-relaxation (S.O.R) method and the SIMPLE
scheme\textsuperscript{14)} to directly obtain velocity and pressure fields.

Coefficients \( f_1 \) and \( f_2 \) depend on the gas and packed bed properties. The gas compressibility makes it necessary for both parameters to be solved iteratively at the same time as the mass velocity and pressure are solved. Pressure and gas density were linked by means of the state equation for ideal gases.

Parameters included in Eqs. (2) and (3), which depend only on solid properties, are the void fraction and the average diameter of particles in the packed bed. The shape factor usually included in \( f_1 \) and \( f_2 \) was equalled to 1 and removed from the equations. The previously mentioned burden distribution model was employed to delimit areas of coke and ore where the parts of \( f_1 \) and \( f_2 \) which depend only on solids properties, were estimated. Figure 3 shows the initial distribution for \( f_1 \) and \( f_2 \) obtained from the charging pattern shown in Tables 5 and 6 for the physical model and taking the gas density for standard conditions. The boundaries between coke and ore have been smoothed by interpolation to improve convergence.

4. Numerical Result for the 1/10 Scale Cold Blast Furnace Shaft Model

The models described above were employed to estimate gas distribution in the physical shaft model for different stages during the burden loading process. In fact, calculations were performed to obtain the gas velocity after dumping each ring of coke and ore.

Figure 4 shows an overview of the gas mass velocity field in the shaft when the loading process has been completed and the burden top layer has descended until the stock line is reached and the top burden layer, thus, corresponds to an ore layer. Burden layers simulated with the burden distribution model have been superimposed onto the mass velocity field. Several features can be pointed out. First of all, in the lower part of the model, there is a triangular zone that simulated the area under the metallic cone of the previously mentioned physical model. As long as the boundary condition for this zone is an isobaric condition, areas of coke present a stronger gas flow than ore areas. In addition, gas flow is stronger near the apex of the cone than at the lower part where the gas flow is almost negligible.

When the physical model was initially designed, this conical zone had the intention of resembling the lower part of...
the blast furnace, i.e. the cohesive zone and dead man. It is obvious that such a design oversimplifies the complexity of these blast furnace areas. But, from the point of view of the interaction between gas and burden distributions in the upper part of the shaft these shortcomings are irrelevant, mainly taking into account that these conditions in the lower part of model remained unaltered during the whole study.

Gas flow through the burden layers present the typical features, with deflexions towards the wall when gas penetrates a coke layer, and turning backs towards the center when gas penetrates an ore layer. The top burden surface presents a smooth mass velocity distribution.

**Figure 5** shows a partial view of the gas mass velocity field. It corresponds with the upper part of the burden after coke ring number 2 has been discharged. Mass velocity on the top surface is regularly distributed.

**Figure 6** shows similar results, this time after coke ring 8 has been discharged. In this case, there is a slight promotion of gas towards the center due to the increase in resistance caused by the coke added.

**Figure 7** shows the mass gas velocity field when the first ore ring (ore ring n°4) is loaded on top of the previous coke layer. As can be seen, gas tries to avoid the ore area due to its low permeability, this causes a sharp increase in gas flow around the zone covered by ore. This local deflexion of the

![Figure 6. Mass velocity field after adding coke ring n°8.](image1)

![Figure 7. Mass velocity field after adding ore ring n°4.](image2)
gas flow causes the coke located in the center to begin to fluidise. This effect is stronger where the next ore ring (ore ring n°5) is discharged. As can be seen in Fig. 8, the coke window in the center of the model is narrower than in the previous case. Moreover, the ore layer that is now formed by the contribution of ore rings 4 and 5 is thicker. Consequently, gas suffers a stronger deflexion. The addition of successive ore rings (ore rings 6 to 9) does not show such a strong gas deflexion. The reason is that ore almost completely covers the previous coke layer, except for the center of the model where coke and ore are mixed due to the partial fluidisation of coke.

It is possible to compare the velocity of gas obtained at the surface of the burden with this mathematical model with the minimum fluidisation velocity for coke particles. The latter can be calculated equalling the drag force of the gas to the weight of the burden particles.\textsuperscript{10,15)}

Figure 9 shows a comparison between minimum fluidisation mass velocity for coke particles and surface mass velocity after discharging ore ring 4 according to the result obtained from the mathematical model. Gas mass velocity reaches a maximum at a distance of roughly 5 cm from the central axis of the model. This value corresponds to the minimum fluidisation velocity for coke particles with a 2.2 mm diameter.

Gas mass velocity decreases towards the center of the model where only particles with a diameter equal to or minus than 1.5 mm could fluidise. In the opposite direction,
gas mass velocity decreases, first sharply because gas collides with the tip of the ore ring and then smoothly as the ore ring becomes thicker.

Beyond 25 cm from the center there is a sharp increase in mass velocity due to the fact that gas has reached the end of the ore ring. The particle diameter that could reach the fluidisation limit will be below 1.5 mm. According to the size distribution for coke employed in the scaled model (see Table 1), fluidisation would be imperceptible in this zone.

Figure 10 shows the same comparison but this time, after adding ore ring 5. As can be seen, the gas mass velocity increases in the center of the model, establishing a new limit for fluidisation in particles with a diameter equal to 2.7 mm.

It is interesting to point out how the model, which was developed to estimate the burden distribution, fails properly describe the burden distribution in the center of the physical model.

The sloped angle of the coke layer was modified to take into account the effect of the gas, as can be appreciated in Figs. 7 and 8, where the profile of the last coke layer has been modified according to such effect. However, neither the burden distribution model can, by itself, simulate the fluidisation of the coke that causes the rising of coke and, eventually, the formation of a narrow circular window of coke in the center of the physical model, nor the area around this window at which coke and ore are mixed.

Coming back to Fig. 2 these phenomena are clearly visible. The observed and calculated profiles for coke ring n°2 do not fit well at the center of the model shaft. The lower boundary of the observed coke layer is roughly two centimetres below the calculated coke layer at the center and they do not fit completely until a distance of ten centimetres from the center is reached. The reason is that coke particles from the previous coke layer have been dragged upward by the air flow, disturbing the ore layer loaded on top of it and causing the formation of the coke window previously described.

This effect should be taken into account as far as it alters the burden distribution foreseen by the plant operator, thus promoting a more central gas flow.

5. Conclusions

The combined models described in this work for burden distribution and gas flow allow for the study of the mutual influence of burden and gas distribution in the upper part of a blast furnace shaft.

For the case studied, it is clear that gas causes significant alterations in the expected burden profiles.

The models can be easily adapted to study other possible burden distributions as long as the model only depends on physical gas properties and on the particular charging pattern employed to load the blast furnace.

Nomenclature

\[ \begin{align*}
\bar{d}_p & : \text{Mean diameter of packed particles (m)} \\
\bar{f}_2 & : \text{Viscous resistance. Defined in Eq. (3)} \\
\bar{f}_3 & : \text{Inertial resistance. Defined in Eq. (4)} \\
\bar{G}_m & : \text{Gas mass velocity (kg/m}^2 \text{s)} \\
\bar{p} & : \text{Gas pressure (Pa)} \\
r & : \text{Radial distance (m)} \\
z & : \text{Axial distance (m)} \\
\varepsilon & : \text{Voidage (–)} \\
\mu_g & : \text{Gas viscosity (kg/m} \cdot \text{s)} \\
\rho_g & : \text{Gas density (kg/m}^3) \\
\end{align*} \]

REFERENCES

1) M. Morin and I. Muchi: Trans. Iron Steel Inst. Jpn., 17 (1977), 330.
2) J. Szekely and M. A. Propster: Trans. Iron Steel Inst. Jpn., 19 (1979), 21.
3) J. Chen, T. Akimaya and J. Yagi: ISIJ Int. 32 (1992), 1259.
4) A. G. S. Steeghs and R. Godijn: Proc. The First Int. Cong. of Science and Technology of Ironmaking, ISIJ, Tokyo, (1994), 198.
5)  J. Yagi: ISIJ Int., 33 (1993), 619.
6)  P. R. Austin, H. Nogami and J. Yagi: ISIJ Int., 37 (1997), 458.
7)  K. Takatani, T. Inada and Y. Ujisawa: ISIJ Int., 39 (1999), 15.
8)  J. A. de Castro, H. Nogami and J. Yagi: ISIJ Int., 42 (2002), 44.
9)  S. Ergun: Chem. Eng. Prog., 48 (1952), 89.
10) J. Jiménez, J. Mochón, A. Formoso and J. S. de Ayala: ISIJ Int., 40 (2000), 114.
11) J. Jiménez, B. Fernandez, J. S. de Ayala, J. Mochón, A. Formoso and F. Bueno: Rev. Metal. Madrid, 34 (1998), (mayo), 158.
12) J. Jiménez: PhD Thesis, Universidad Nacional de Educacion a Distancia, Madrid, (1998).
13) Blast Furnace Phenomena and Modelling, ed. by ISIJ, Elsevier Applied Science, New York, (1987), 327.
14) J. H. Ferziger and M. Peric: Computational Methods for Fluid Dynamics, Springer-Verlag, Berlin, (1997), 159.
15) C. Wen and Y. Yu: AIChE J., 12 (1966), 610.