# NUMERICAL MODELING OF THE INTERNAL STATE OF BLAST FURNACE [1]

*Sami-Alex Zaïmi* [2]
*Dominique Sert* [2]
*Gerard Danloy* [3]
*T. Buhles* [4]
*G. Dauwels* [5]
*Jean-Louis Eymond* [6]
*Guilhaume Lesoin* [7]
*Thiago Rabelo Nunes Campos* [8]

## Abstract

The main objective of this work is to present two numerical tools developed by the Arcelor Mittal Group through Arcelor Research and CRM (Centre for Research in Metallurgy). The basic aim of these models is to monitor the blast furnace's internal state through the calculation of the cohesive zone's position and shape. The simulations are based in the operational data of several blast furnaces of Arcelor Mittal in Europe. To describe the internal state of the reactor, there are two numerical models implemented in Arcelor Mittal's blast furnaces in Europe: Mogador and ZAP, models developed, respectively, by CRM and Arcelor Research. In the present work, typical applications of these models were presented. In these cases, the prediction of troubles in the furnace operation and the consequences originated by operational changes was done through their use. The efficiency of the models was confirmed through the comparison between their results and the operational parameters of blast furnaces which they are implemented. The several cases studied showed that the predictions carried out by the models agreed with the results obtained through the available probing methods to each blast furnace took into account. Moreover, one model got to predict troubles resulting from changes on the operational conditions. The main results of this work are graphics and profiles that confirm the usefulness and show the viability of the application of numerical models as tools to help the operation of blast furnaces.

**Key words:** Blast furnace; Mathematical modeling; Cohesive zone.

## MODELAMENTO COMPUTACIONAL DO ESTADO INTERNO DO ALTO FORNO

## Resumo

O principal objetivo deste trabalho é apresentar duas ferramentas numéricas desenvolvidas pelo grupo Arcelor Mittal através da Arcelor Research e do CRM (Centro de Pesquisas Metalúrgicas). O objetivo básico destes modelos é monitorar o estado interno do alto-forno através do cálculo da forma e da posição da zona de amolecimento e fusão. As simulações são baseadas em dados operacionais de diversos altos-fornos da Arcelor Mittal na Europa. Para descrever o estado interno do reator, existem dois modelos numéricos implementados nos altos-fornos da Arcelor Mittal na Europa: Mogador e ZAP, desenvolvidos respectivamente pelo CRM e Arcelor Research. No presente trabalho, aplicações típicas destes modelos foram apresentadas, como por exemplo, a previsão de distúrbios na marcha do forno e as conseqüências geradas por mudanças operacionais. A eficiência dos modelos foi confirmada através da comparação entre seus resultados e parâmetros operacionais dos altos-fornos nos quais eles estão implementados. Os diversos casos estudados mostraram que as previsões realizadas pelos modelos concordaram com os resultados obtidos através dos métodos de sondagem disponíveis para cada alto-forno considerado. Além disso, um dos modelos conseguiu prever distúrbios resultantes de modificações nas condições operacionais. Os principais resultados deste trabalho são gráficos e perfis que confirmam a utilidade e mostram a viabilidade da aplicação de modelos computacionais como ferramentas para auxiliar a operação dos altos-fornos.

**Palavras-chave:** Alto-forno; Modelamento computacional; Zona de amolecimento e fusão

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[1] *Technical contribution to XXXVII Ironmaking and Raw Materials Seminar, September 18-21, 2007, Salvador – BA, Brazil*
[2] *Research Engineer, Arcelor Research, Maizières-les-Metz, France.*
[3] *Research Engineer, Centre for Research in Metallurgy, Liège, Belgium.*
[4] *Arcelor Bremen, Bremen, Germany.*
[5] *Arcelor Sidmar, Gent, Belgium.*
[6] *Arcelor Atlantique, Dunkerque, France.*
[7] *Arcelor Méditerranée, Fos-sur-Mer, France*
[8] *ABM's Member. Undergraduate Student in Metallurgical Engineering. Federal University of Minas Gerais. Arcelor Research's Trainee, Maizières-les-Metz, France.*

## 1 INTRODUCTION

The knowledge of the cohesive zone shape and position in the blast furnace is a fundamental issue for the operators, because it acts as a gas distributor, which in turn impacts remarkably the productivity, hot metal quality and reducing agents consumption of the apparatus. Besides, the operator has no full control of all inputs and what they become within the furnace, since no on-line continuous measurement is possible inside.(1)

To determine the cohesive zone, two different – yet complementary – tools have been developed and implemented in Arcelor Group blast furnaces: Mogador, designed by CRM;(2) and ZAP, designed by Arcelor Research.(3) These models provide to the operators an access to the internal state of the blast furnace, notably the image of the cohesive zone, which makes it possible to improve the gas flow monitoring. The respective properties and advantages of these models are reviewed in this paper.

## 2 MODELS PRESENTATION

### 2.1 The Mogador Model

#### 2.1.1 Principles

This 2D model calculates by finite differences the internal state of the blast furnace at steady state, in terms of chemical and thermal distributions, by simulating the essential phenomena involved in the process (gas flow, solid flow, heat transfer, indirect ore reduction, carbon gasification, water gas shift, softening and melting).

The main inputs are the burden distribution (layers thickness, composition, particle size), the bosh gas properties (flow rate, composition, flame temperature), and some process data (heat losses, pig iron composition…).

After little iteration that do not exceed 30 minutes, the model outputs maps of temperature, velocity and composition of the gas, solid and liquid phases; as well as the position of the layers and of the cohesive zone. Figure 1 shows the internal routine of Mogador.

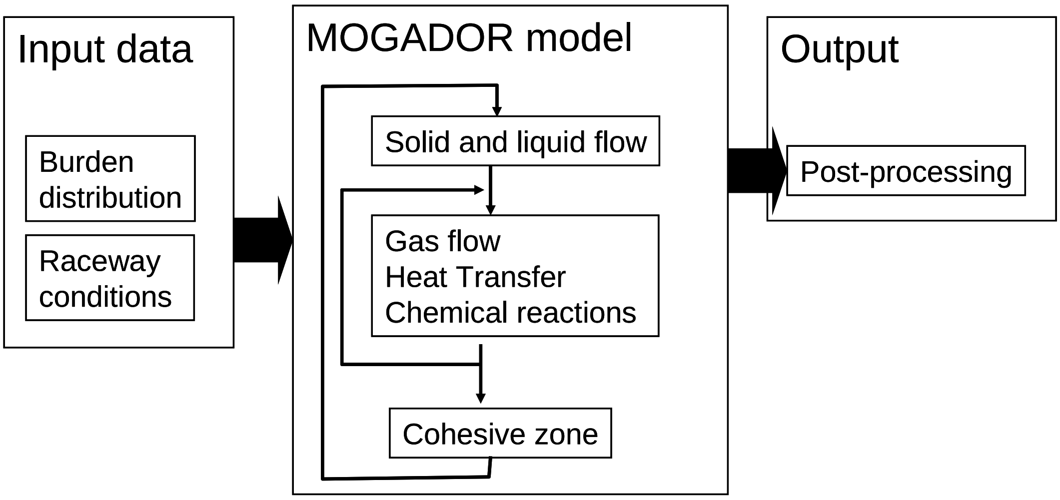


**Figure 1** – Mogador internals

Mogador has been calibrated by means of vertical probing and gas tracing experiments, performed at BF-B of Arcelor Sidmar.

### 2.1.2 Industrial implementation

Mogador being a steady state model, it is recommended to run it on a 24 hours basis. In practice, it is run either every day, either every shift, using in both cases the averaged data of the last 24 hours. However, in most plants, the burden distribution is calculated with the last charging pattern.

The model has been validated using multipoint vertical probing trials at Dunkerque, Bremen and Patural blast furnaces. The results match rather well with available on-line measurements, such as top gas analysis and temperature or wall gas pressure profiles. A good correlation has been found between the calculated height of the cohesive zone and the measured silicon content of the hot metal.

Some numerical constants required some tuning, among them the heat transfer coefficients with the wall and the bed porosity. At Dunkerque, these transfer coefficients are automatically recomputed from the actual heat loss measurements.

## 2.2 The ZAP Model

### 2.2.1 Principles

This original tool aims at positioning the cohesive zone, only, from process data measurements and some “rules”, which is probably enough for daily process monitoring.

These “rules” are simply a computer transposition of the main existing ideas concerning the relationships between process parameters and cohesive zone characteristics, among them:

- Existence of a link between the CO efficiency profile at the above burden probes (gas distribution indicator), and the shape of the softening line of the cohesive zone (roughly, one is the mirror of the other);
- Existence of a link between the C/(C+O) profile at the top (burden distribution indicator), and the relative thickness of the cohesive zone along the radius of the furnace;
- Existence of a link between the average level of the cohesive zone and the silicon content of the hot metal.

In order to be quantitative, the aforementioned relationships have to be calibrated for each blast furnace by means of at least one multipoint vertical probing exercise.

The core part of the model is based on a 1D heat and mass exchanger in the dripping zone, which finds its appropriate height (hence the mean level of the cohesive zone) by matching the computed and measured hot metal temperatures. This model takes into account a varying amount of solution loss taking place below the cohesive zone (which is a tuning parameter), and the experimental relationship between hot metal silicon content and temperature. Figure 2 shows internal routine of ZAP.

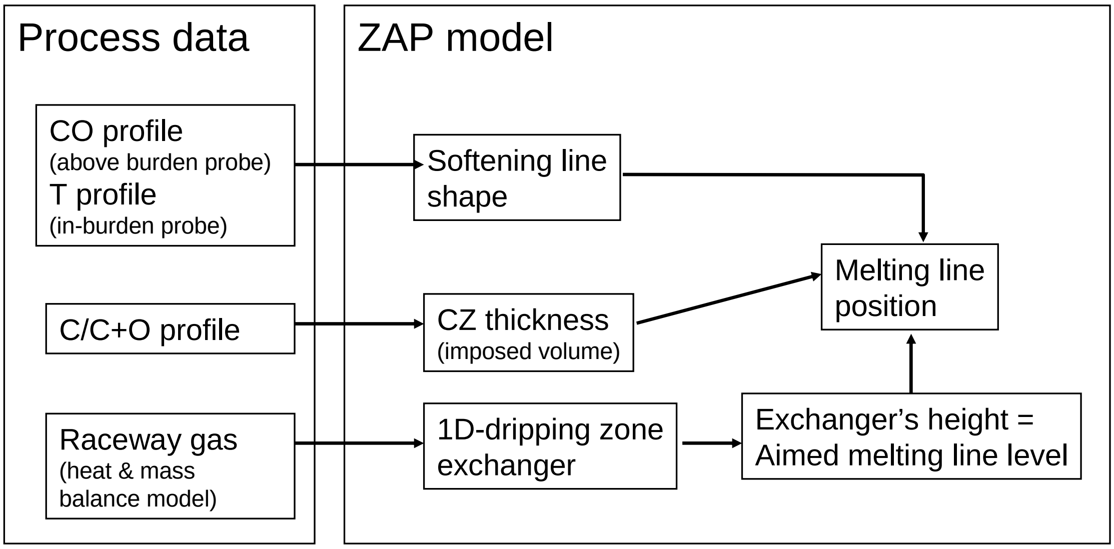


**Figure 2** – ZAP internals

### 2.2.2 Industrial implementation

The implementation of ZAP in a new plant requires the availability of an on-line heat and mass balance model (blast conditioning, hot metal temperature), in-burden (temperature) or above burden (CO efficiency) probes, and a profilemeter (for the C/C+O profile) or a reliable burden distribution model.

Note that the frequency of use of ZAP can span from day, through shift, up to cast time basis; and be used in each vertical slice of the furnace that contains a horizontal probe. The computation time takes only a few minutes.

## 3 INDUSTRIAL PRACTICE AND RESULTS

### 3.1 Overview

In an industrial daily use, both models are used to monitor the height and shape of the cohesive zone, the volume of the coke reserve zone and the minimal distance between the cohesive zone and the dead-man. These indices are used to characterise the thermal state of the lower part of the blast furnace, along with usual on-line measurements. In case of confirmed unfavourable drift, specific actions are taken, such as the dump of an additional skip of coke.

The evolution of the cohesive zone can be monitored with time, and confronted to other on-line measurements, like above or in-burden probes, which indicates if the gas flow is rather central or peripheral; or wall gas pressure, which indicates the position of the root of the cohesive zone; or finally the silicon content of the hot metal.

The industrial interests of such models are:

- To check everyday that the applied operating conditions have had the desired results in terms of gas distribution;
- To apply with a much higher confidence a set of corrective actions in case of wrong response, or to keep with actual actions in case of good response of the blast furnace.

Indeed, either Mogador or ZAP models were used to prepare and monitor unusual or abnormal operations, such as a de-scaffolding, a two hot-stoves operation, or a slowing down - recovering sequence. However, both models are better used as on-line tools for instantaneous process monitoring and analysis (so called “diagnosis mode” as opposed to “predictive mode”).

Moreover, the models proved to be very efficient pedagogical tools for training the operators, for illustrating guidance books with typical internal images, and for completing classical diagnosis tools that already exist in the control room.

## 3.2 Illustration of Mogador

In this part, we illustrate the use of Mogador with three multipoint vertical probing trials that occurred on different blast furnaces belonging to Arcelor Mittal Group, namely Dunkerque #4, Bremen #2 and Patural #3. The Table 1 summarises the operation data at the day of the trial.

**Table 1** – Blast furnaces operation data for Mogador

| Label | Unit | Dunkerque #4 (22/01/04) | Bremen #2 (01/06/05) | Patural #3 (05/07/05) |
|---|---|---|---|---|
| Production | thm/d | 8760 | 6984 | 3840 |
| Coke rate | kg/thm | 305 | 310 | 267 |
| Coal rate | kg/thm | 187 | 178 | 214 |
| Blast rate | kNm3/h | 347 | 250 | 132 |
| Blast T. | °C | 1175 | 1221 | 1172 |
| Blast $O_2$ | % | 23.9 | 24.2 | 25.5 |
| Flame T. | °C | 2086 | 2038 | 2074 |
| $\eta_{CO}$ | % | 50.4 | 51.3 | 51.3 |
| Pig iron T. | °C | 1505 | 1457 | 1483 |

The Figure 3 represents the cohesive zones, as computed by MOGADOR. We have also represented the region bounded by the 400°C and the 700°C isotherms, where the ore degradation might occur, and the region around the raceway with a temperature higher than the flame temperature minus 100°C.

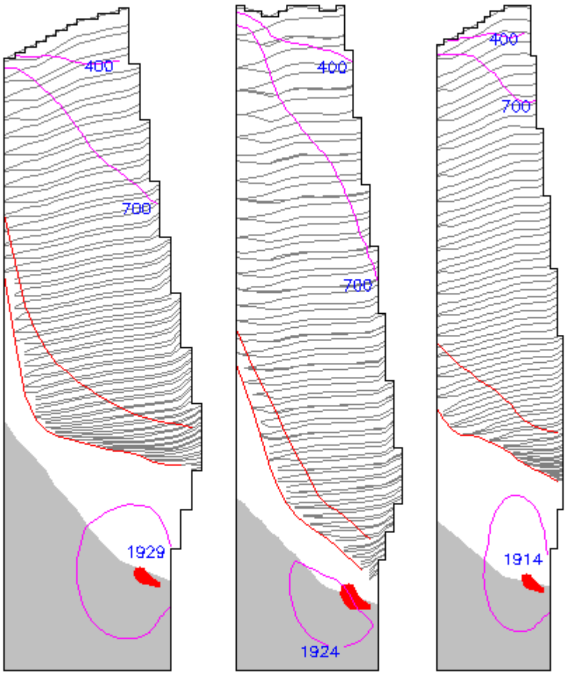


**Figure 3** – Cohesive zones computed by Mogador at Dunkerque #4 (left), Bremen #2 (middle) and Patural #3 (right) blast furnaces.

## 3.3 Illustration of ZAP

In this part, we illustrate the use of ZAP on two different blast furnaces belonging to Arcelor Mittal Group, namely Fos #1 and Bremen #2. The Table 2 gathers some operation data for the first blast furnace, the operating conditions of the second one being already described in Table 2.

**Table 2** – Blast furnaces operation data for ZAP

| Label | Unit | Fos #1 (24/12/02) |
|---|---|---|
| Production | thm/d | 6094 |
| Coke rate | kg/thm | 330 |
| Coal rate | kg/thm | 157 |
| Blast rate | kNm3/h | 224 |
| Blast T. | °C | 1123 |
| Blast $O_2$ | % | 25.3 |
| Flame T. | °C | 2158 |
| $\eta_{CO}$ | % | 50.0 |
| Pig iron T. | °C | 1471 |

The Figure 4 represents the cohesive zones as computed by ZAP. We have added on these figures the minimal distance between the melting curve and the assumed deadman. The upper (resp. lower) horizontal line represents the average level of the softening (resp. melting) line.

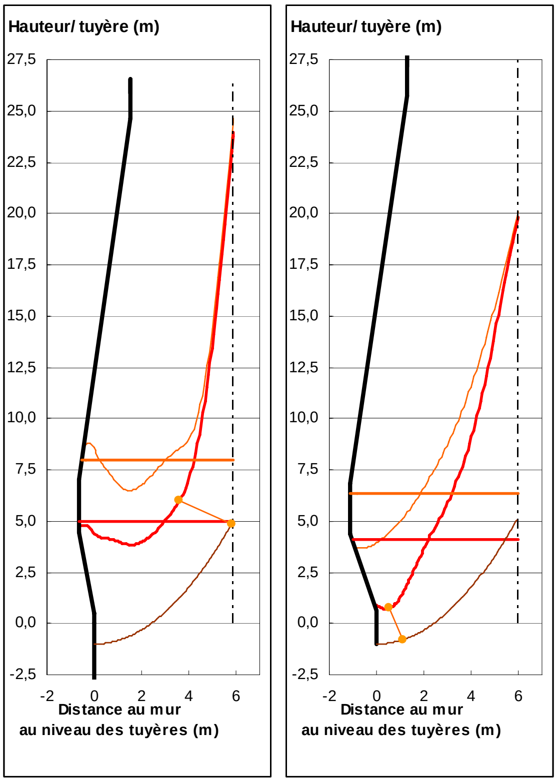


**Figure 4** – Cohesive zones computed by ZAP at Fos #1 (left) and Bremen #2 (right) blast furnaces

## 3.4 Correlations with Process Data

A series of correlations were investigated with Mogador and ZAP, between the height of the cohesive zone and some process parameters, such as:

- The hot metal silicon content (Figure 5);
- The hot metal temperature (Figure 6);
- The flame temperature (Figure 7);
- The furnace productivity (Figure 8).

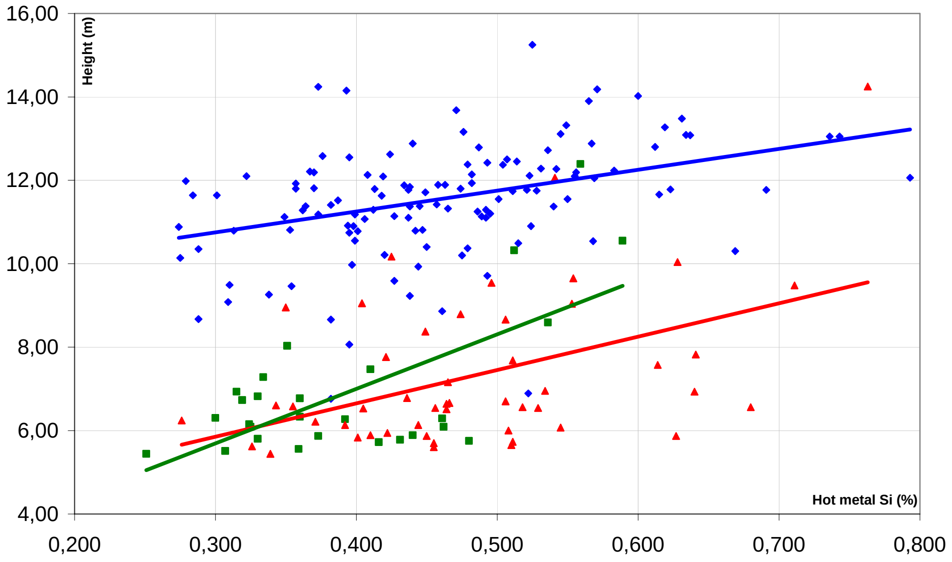


**Figure 5** – Average level of the cohesive zone computed by MOGADOR at Dunkerque (in m) vs. the hot metal silicon content (in %), at three different periods

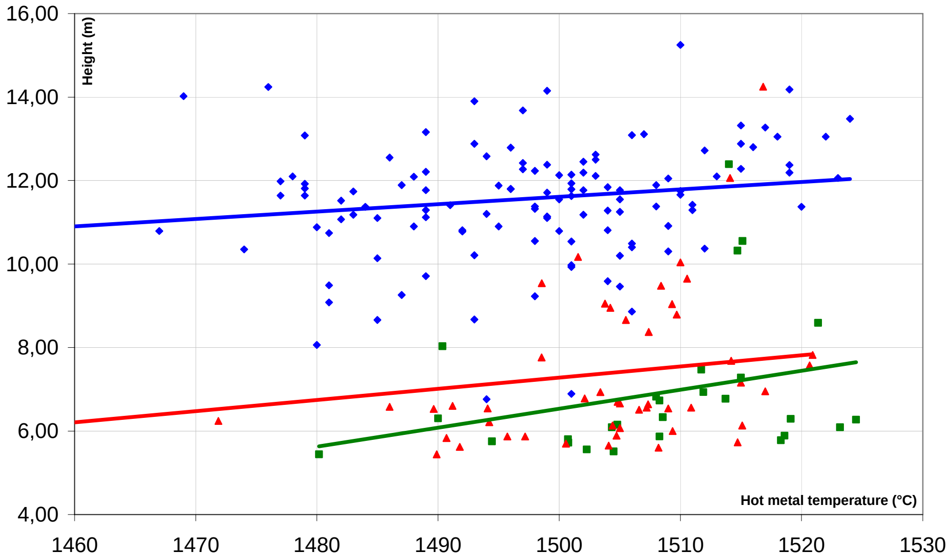


**Figure 6** – Average level of the cohesive zone computed by Mogador at Dunkerque (in m) vs. the hot metal temperature (in °C), at three different periods

For instance, the higher the cohesive zone, the higher the height of the lower chemical exchanger in the dripping zone, then the higher the silicon content in the hot metal and the hot metal temperature. However, the height of the cohesive zone seems more related to the silicon content of the hot metal than its temperature.

It was also observed that relatively large fluctuations of the flame temperature (between 2050°C and 2250°C) induce variations of the average level of the melting line of about 1.50 m, and a variation of the hot metal temperature of 100°C.

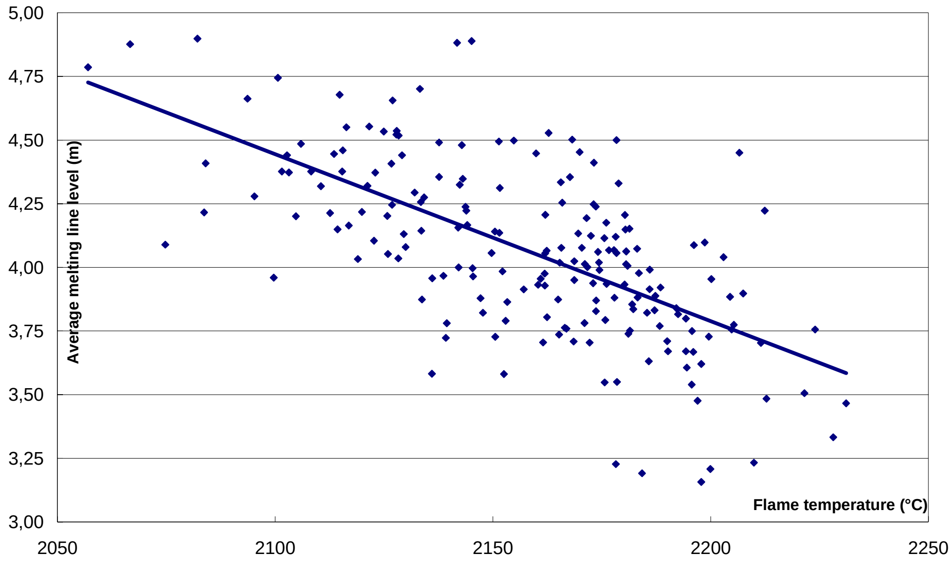


**Figure 7** – Average level of the melting line computed by ZAP at Fos (in m) vs. the flame temperature (in °C).

The average level of the cohesive zone tends to rise when the productivity decreases. This phenomenon can be interpreted as a decrease of the surface of exchange between gas and liquids, which then reduces the efficiency of the heat transfer between them.

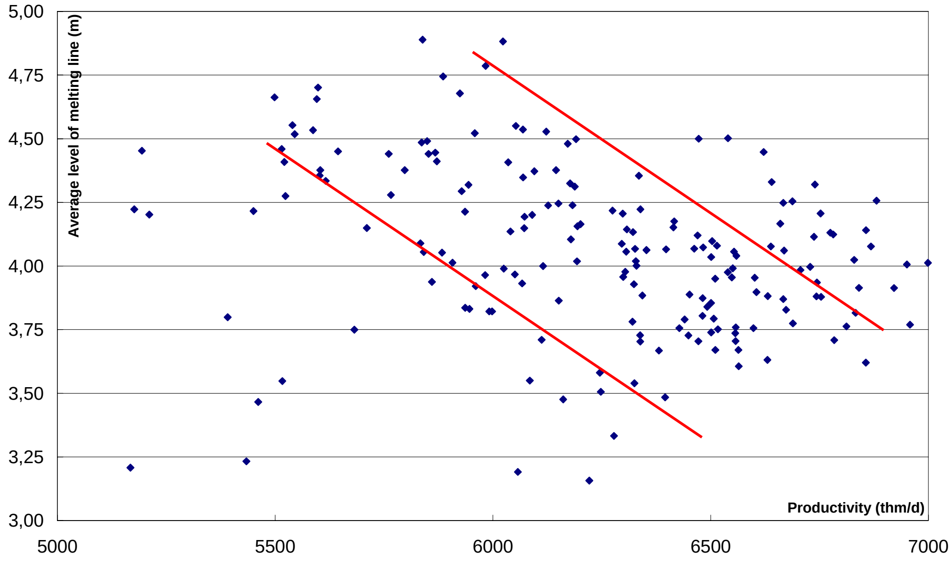
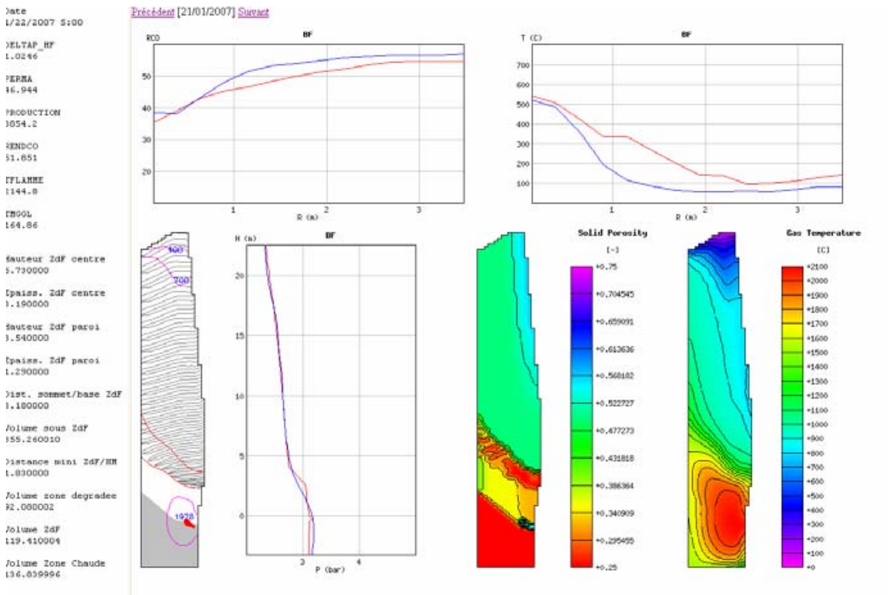


**Figure 8** – Average level of the melting line computed by ZAP at Fos (in m) vs. the productivity (in thm/d).

## 3.5 Industrial Application

The images provided by both models are available either to the operator in the control room or to the process engineer, or at the morning's meeting for discussion as can be seen in the Figures 9 and 10.



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FLAMME
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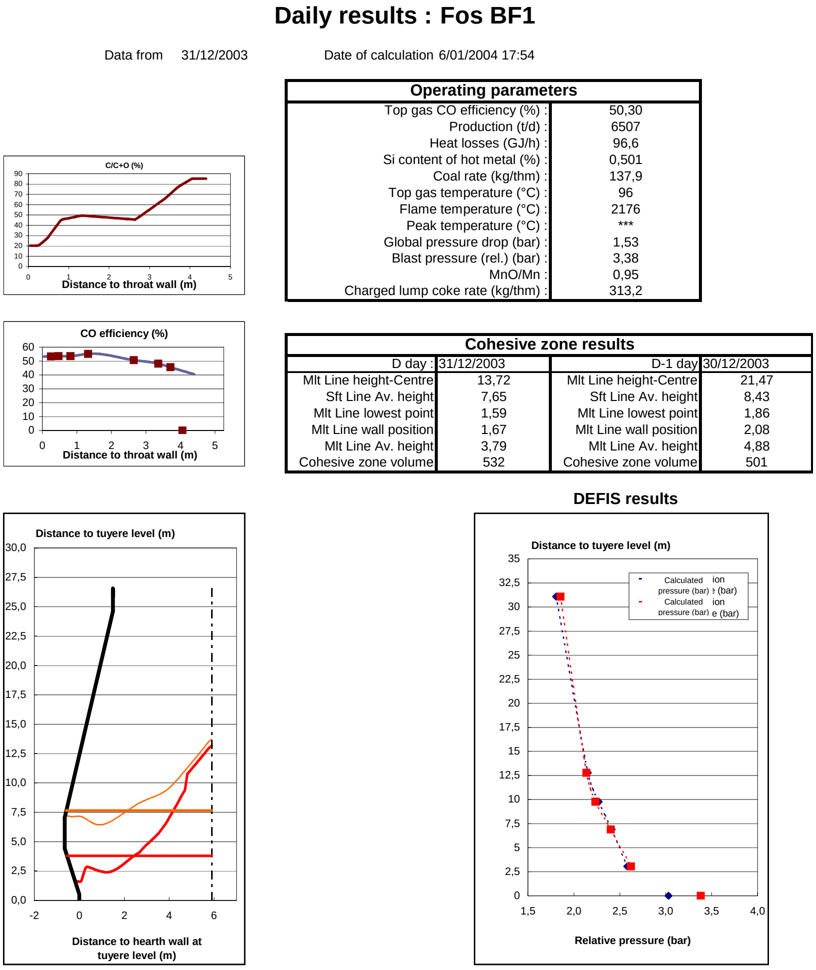
**Figure 9** – Screenshot of Mogador monitoring at Patural #3.



## Daily results : Fos BF1

Data from 31/12/2003 Date of calculation 6/01/2004 17:54

| Operating parameters | |
|---|---|
| Top gas CO efficiency (%) : | 50,30 |
| Production (t/d) : | 6507 |
| Heat losses (GJ/h) : | 96,6 |
| Si content of hot metal (%) : | 0,501 |
| Coal rate (kg/thm) : | 137,9 |
| Top gas temperature (°C) : | 96 |
| Flame temperature (°C) : | 2176 |
| Peak temperature (°C) : | *** |
| Global pressure drop (bar) : | 1,53 |
| Blast pressure (rel.) (bar) : | 3,38 |
| MnO/Mn : | 0,95 |
| Charged lump coke rate (kg/thm) : | 313,2 |

| Cohesive zone results | | | |
|---|---|---|---|
| D day : | 31/12/2003 | D-1 day | 30/12/2003 |
| Mlt Line height-Centre | 13,72 | Mlt Line height-Centre | 21,47 |
| Sft Line Av. height | 7,65 | Sft Line Av. height | 8,43 |
| Mlt Line lowest point | 1,59 | Mlt Line lowest point | 1,86 |
| Mlt Line wall position | 1,67 | Mlt Line wall position | 2,08 |
| Mlt Line Av. height | 3,79 | Mlt Line Av. height | 4,88 |
| Cohesive zone volume | 532 | Cohesive zone volume | 501 |

DEFIS results

**Figure 10** – Screenshot of ZAP monitoring at Fos and Dillingen.

The figures 9 and 10 show the usefulness of the images provided by Mogador and ZAP to the operational team, because through these profiles, the blast furnace internal state can be continuously monitored.

## 4 CONCLUSION

The models Mogador and ZAP improve the analysis and the understanding of the process of the blast furnace, thanks to the computation of the height and shape of the cohesive zone, and some correlations that could be obtained with selected process data. In daily use, the models confirm the actions taken. In the future, these models would save the need for expensive trials and probes.

Within Arcelor Mittal Group, MOGADOR is operational at Gent BF-A & B, Dunkerque #4, Bremen #2 and Patural #3 blast furnaces, whereas ZAP is operational at Fos #1 & #2, Bremen #2 and Dillingen #5 blast furnaces.

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