Results and Visualization from the First Campaign in LKAB's Experimental Blast Furnace in Luleå, Sweden

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Key Words: blast furnace excavation, iron structure types, blast furnace reduction visualization

INTRODUCTION

Industrial trials in production furnaces, as a tool in the blast furnace pellet development process, are expensive, involve high risk and are difficult to evaluate. Standard laboratory metallurgical tests are, however, not sufficient for evaluating new blast furnace pellets. With this background, the LKAB board decided in October 1996 to invest 52 million Swedish kronor (approx. 6.5 million US$) in a pilot scale experimental blast furnace, for pellet development purposes. The construction of the furnace took one year and it was built at the MEFOS premises in Luleå, Sweden. The furnace was fully financed and is owned by LKAB. The blast furnace is planned to be in operation for 2 campaigns per year, each for a duration of 4-6 weeks. To date, 5 campaigns have been carried out.

The main benefits of a pilot scale furnace compared to laboratory tests are the generation of a complex reduction gas including alkali, sulfur and zinc, the relative movement of the burden material and the presence of coke (aiming at a fuel rate close to production furnaces).

Apart from avoiding expensive running disruptions, one advantage compared to a production furnace is the possibility to quench and dissect the furnace. To date, the experimental blast furnace has been quenched at the end of each campaign. The main objective for quenching and dissecting the furnace is to provide material for detailed studies on the state of the furnace and properties of the pellets at various stages of reduction. This paper describes the task of transforming the physical pellet samples taken out during dissection, into such information.

The first stage of this transformation is to decide which data should be registered when characterizing the pellet samples and this is determined by the information sought. Interesting aspects when developing new pellets are for example the behavior of additives (slag-formers and binders), crack formation and pellet strength during reduction. These aspects must, however, be investigated relative to how the reduction of the iron oxides proceeds.

A dissection of the pilot furnace typically results in close to 250 pellet samples from various sample points throughout the furnace. From each sampling point, a number of pellets must be studied, adding up to about 2000 pellets. Prior to quenching, a number of small baskets containing pellets or burden mixtures of special composition, are added. Investigating these results in, at least, an equal number of samples. Initially, work has been concentrated on "only" looking at the 2000 pellets from the layer sample points. Each pellet contains a lot of information and has been examined to provide basic data. This data is then combined to supply information about the system.
Samples from one dissection of the experimental blast furnace have been studied. The furnace was operated on standard LKAB olivine pellets prior to quenching. Considering only the iron oxides and their reduction, we distinguish between 12 different structure types and their distributions within the pellets are quantified. This obviously result in an enormous amount of data that somehow must be represented such that the information contained in the data is readily available and understandable. The following sections concentrate on the process of obtaining data from the individual pellets to visualizing the information contained in the data in a meaningful way.

EXPERIMENTAL

The blast furnace, shown in Figure 1, has three tuyeres and a diameter at the tuyere level of 1.2m. The working volume is 8.2m³. The hot blast is produced in pebble heaters capable of supplying 1300°C of blast temperature. The furnace is designed for operating with a top pressure of 1.5 bar. It has a bell-type charging system with movable armor. The coal injection system features individual control of coal flow for each tuyere. The gas cleaning system consists of a dust catcher and a wet electrostatic precipitator. A tapping machine with drill and mud gun was installed. The blast furnace is well equipped with sensors and measuring devices, and an advanced system for process control. Probes for taking material samples from the furnace during operation have also been developed. More details regarding the furnace operations were reported by Dahlstedt et al. (1).

Fig. 1. Schematic of the pilot blast furnace

Campaign Details

The samples discussed further in this paper are from the first furnace campaign run in October/November 1997. During this campaign, a fuel rate of only 515 kg/THM was reached. Since coal injection was not in operation, high moisture was used to increase hydrogen in the reduction gas to a typical level for furnaces with coal injection. In Table I, the main operating parameters before shutdown are listed. At the end of the campaign, when a stable operation had been reached, the furnace was quenched with nitrogen from the top down. Within minutes, reducing gases are flushed out of the furnace. The temperature of the outlet gas decreases below 600°C within twelve hours of the stop. The furnace is left to cool to ambient temperature for about two weeks and is then carefully excavated layer-wise from top to bottom.
Table I: Furnace operating parameters before shut-down, November 1997.

<table>
<thead>
<tr>
<th>Productivity (T/m³24h)</th>
<th>4.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burden</td>
<td>MPBO Pellets</td>
</tr>
<tr>
<td>Total (kg/THM)</td>
<td>1396</td>
</tr>
<tr>
<td>Quartzite (kg/THIM)</td>
<td>10</td>
</tr>
<tr>
<td>Limestone (kg/THIM)</td>
<td>50</td>
</tr>
<tr>
<td>LD-slag (kg/THM)</td>
<td>51</td>
</tr>
<tr>
<td>Coke (kg/THIM)</td>
<td>515</td>
</tr>
</tbody>
</table>

Blast parameters

| Temperature (°C) | 1208 |
| Moisture (g/Nm³) | 40   |
| Top gas          |      |
| Temperature (°C) | 121  |
| Pressure (Bar)   | 0.67 |
| ηCO (%)          | 48.4 |
| H₂ (%)           | 2.4  |

Hot metal

| Temperature (°C) | 1416 |
| C (%)            | 4.5  |
| Si (%)           | 0.66 |
| S (%)            | 0.065|

Slag

| Volume (kg/THM) | 146  |
| MgO (%)         | 17.0 |
| Al₂O₃ (%)       | 12.8 |
| CaO/SiO₂        | 0.84 |

Pellets Sampling and Preparation

During the furnace excavation, samples from both the pellet- and coke-layers were taken. This study, however, dealt exclusively with the pellet layer samples. For each of the 25 separate pellet layers throughout the furnace (down to the tuyers), samples from 10 take-out points were systematically taken. A schematic of the take-out point layout over the blast furnace cross-section, is shown in Figure 2.

Fig. 2. Furnace cross-section schematic. The circular marks denote sample takeout points 0-9. The square marks denote the three tuyere positions.

From each take-out point, a sample of seven pellets was prepared for micro analysis. These seven pellets were mounted together and the mount subsequently polished, to display the largest pellet cross sections. To distinguish between co-existing Fe₃O₄ and FeO, samples potentially containing both of these oxides were etched for 20 seconds in a 5% HF in H₂O solution.

Pellet Characterization

An image of each mounted sample was subsequently captured using a Kontron ProgRes 3012 digital camera with a macro lens, coupled to a computer. As illustrated by Figure 3, each pellet consisted of one or more visually distinguishable "zones", which display different degrees of reduction. In the first stage of the characterization work, reported in this paper, only the iron structures were studied and the phases and features of the slag-forming oxides in the pellets were not considered. Through optical microscopy, the approximate distribution of FeOₓ and Fe structures in each zone of each sample pellet, was estimated. The structures
observed could be categorized into 12 different types, such as coarse-, medium- and fine-grained hematite, "new" and "old" magnetite, different structures of the metallic iron and so forth. These types are illustrated and described in Appendix 1.

Fig. 3. Image of pellet mount from sample point 5 in layer 3, obtained with a digital camera.

Pellet Structure Quantification

After acquiring images of each sample mount, the zone boundaries (for the pellet zones discussed above) were identified and the zone areas determined using the interactive functions in Zeiss' KS300 Image Analysis System. From the zone areas established through image analysis, in conjunction with the distribution of structures determined by microscopy, the total distribution of structures in each pellet was obtained. From these results, the total reduction degree for each pellet could also be calculated.

Visualization and Reporting Procedure Development

As earlier indicated, interpretation of a large and diverse set of measured data can be a very difficult job. The transformation from data to information is time consuming and if not done in an appropriate manner, valuable information may be lost or underlying mechanisms and effects not shown. By using a "top-down" interpretation approach where the system as a whole is first observed, and from which effects downwards can be studied, information can easily be linked and put in perspective. This approach results in quicker interpretation because it gives a first-impression and understanding of the whole, thus it is more intuitive where to look for further information.

The pellet characterization data was entered into a carefully designed database, forming the basis for a data ordering, reporting and visualization system. The database design enables the possibility to extract any information in a predefined manner and effects to be studied top-down.

The present system requires that one original database containing raw data is running on a server. Distributed clients may then connect to the server and get the available information. Access restrictions are defined on server-side so that different users may have different access rights. The LKAB visualization tools contain separate components: The database, web-server components accessing the database, a web-browser with integrated support for 3d-visualization.

The system is very flexible concerning changes in the different components. The database is designed to allow changes and additions without destroying the query interface. The visualization tool is generic and accepts any objects/data for visualization not restricted to one single application. The web-server is based on HTTP/1.1.

The browser is a superset of the standard Microsoft Internet Explorer with the possibility to browse any Internet web page. In addition it has a proprietary OpenGL-based interface with a scripting
language. This "add-on" is capable of communication directly with the web-server and is updated through inline scripting in the HTML-document. This makes it possible to browse information through clicking on 3D objects and get information about this object as a web page, or a different 3D-setting.

RESULTS AND VISUALIZATION

As indicated above, the furnace excavation results may be visualized in several different manners. One type of visualization is shown in Figure 4, which is four frames of the 3-D visualization application, illustrating the points of presence (>2% of total pellet volume) of the different iron oxides, \( \text{Fe}_2\text{O}_3 \), \( \text{Fe}_3\text{O}_4 \), \( \text{FeO} \) and metallic \( \text{Fe} \), throughout the furnace. It should be pointed out that this figure does not show individual structures, but all hematite structure types as \( \text{Fe}_2\text{O}_3 \), all magnetite structure types as \( \text{Fe}_3\text{O}_4 \), etc.

As seen from Figure 4, hematite in its various forms is the most prevalent iron oxide in the upper two layers of the furnace although some reduction of hematite to magnetite has started to take place already in layer 2. In layer 3 there are substantial amounts of newly formed magnetite present, the hematite and magnetite being approximately equal. Interestingly, in a few pellets in layer 3, wüstite has started to form, indicating that the temperature is higher than that required for stabilisation of wüstite (~570°C). Already in layer 5, essentially all hematite has disappeared and magnetite and wüstite are the two, equally predominant phases. From layer 6 and down, wüstite dominates the furnace picture and the wüstite zone remains very stable all the way down to layer 18. As demonstrated by the figure, wüstite is the dominant iron oxide as deep down in the furnace as layer 12. Although metallic iron makes an appearance in a few pellets already in layer 9, it is not until in layer 15 that wüstite and metallic iron are equally represented in the pellets. There is however traces of magnetite still left in pellets as far down as layer 17.

![Fig. 4. 3-D visualization of the presence of Fe\(_2\)O\(_3\) (upper left), Fe\(_3\)O\(_4\) (lower left), FeO (upper right) and Fe\(_{\text{net}}\) (lower right) in the furnace.](image)

When studying the structure types present in the pellets throughout the furnace a little closer, there are a few observations that are of particular interest. The bar graph in Figure 5, for example, illustrates the average percentage distribution of structure types present in sample point 1 in all layers of the furnace.
Fig. 5. Average percentage distribution of structure types in sample point 1 throughout the furnace layers 1-24.

While hematite in most sample points quickly disappears and is reduced to magnetite, it is seen from the graph in Figure 5 that small remains of hematite occur as far down in the furnace as layers 5-6 (~3.2 m above the tuyers). Generally, these remains consist of the coarse grained, “patch” hematite (structure type 1), indicating that this type of hematite is the most difficult to reduce.

During the microscopic investigations, it was observed that this hematite structure always occurred further towards the center of the pellets than the medium and fine-grained hematite and often in conjunction with “old” magnetite, which had not been oxidized in the pellet-firing kiln.

It may be suggested that the presence of the large grained hematite is due to oxidization during the pellet firing process, which was taking place under too high temperature and an atmosphere deficient in oxygen. Remains of old magnetite and coarse grained hematite in the pellets result in slow reduction in the blast furnace.

As seen from Figure 5, “new” magnetite (structure types 5 and 6) starts to form already in the very upper parts of the blast furnace, while hematite and old magnetite are still the predominant structures. The “new” magnetite is, initially, mainly present as matrix to the hematite or as separate grains of mixed but smaller size in an outer pellet shell. From layer 2-3 (~3.8 m above the tuyers) until
layer 5 (~3.3 m above the tuyers) the new magnetite is the most dominant until the temperature and reducing atmosphere favors wüstite. Magnetite from then on occurs almost only as matrix to the wüstite (structure type 7) and only in very few pellets, close to the pellet center, in the form of larger separate grains. There are, however, traces of magnetite still present in layer 17 (~1.3 m above the tuyers).

As illustrated in Figure 5, as well as in Figure 4, wüstite (structure type 8) becomes the most predominant iron structure already in layer 6, (~3.1 m above the tuyers). Initially the wüstite evolves from reduction of small magnetite grains, forming a kind of matrix to larger magnetite grains, or a thin shell on the surface of the pellets. Wüstite then quickly becomes the dominant structure, forming a homogenous de-fragmented pellet phase.

As also seen from Figure 5, from layer 19 and deeper in the furnace, metallic iron is the dominant state. Although traces of metallic iron are present as far up in the furnace as layer 9 - in the form of single snowflake-like crystals (structure type 9) - it is not until in layer 20, ~1 m above the tuyers, that the iron shows clear tendencies towards sintering (structure type 11). One interesting observation is that many pellets seem to have sintered or melted iron in the center while a very porous iron structure is retained in the outer part of the pellet. Since the sintered or melted iron is often observed together with small rests of wüstite in the pellet center, it could be speculated that this may be due to the lower melting point of the FeO/Fe mixture than that of the pure Fe, as indicated by the Fe-O phase diagram. From layer 20 and on, the iron quickly sinters/melts together, forming a more homogenous iron structure (structure type 12) within each original pellet. It is, however, not until layer 23-24 (just above the tuyers) that the pellets melt together and individual pellets can no longer be distinguished, indicating that the blast furnace cohesive zone has been reached.

In Figure 6, another system visualization feature is illustrated, which is the calculated degree reduction in the furnace.

Fig. 6. 3-D visualization of average degree reduction in the furnace (light to dark means increase in degree reduction).

Following earlier observations, it is clear that very little reduction has taken place in layer 1 and it can tentatively be concluded that the pellets from layer 1 closely resembles those of the charge material. Moving into layer 2, the degree reduction is still very low but appears fairly uniform as no obvious reduction pattern can be observed. This may indicate that the gas/burden distribution is relatively even in this part of the furnace.

Already in layer 3, it is obvious that there are differences in the degree of reduction in pellets from different sample point locations. Pellets sampled from the middle of the furnace, especially from sample point 3 but also from sample points 2 and 4, are notably less reduced than pellets sampled
from the outer parts of the furnace. This behavior is prominent deep down in the furnace and the least reduced pellets still come from the middle of the furnace in layer 19. This can be explained from the fact that the furnace at this time was wall working. During this first excavation, it could also be observed from the shape of the pellet and coke layers that the burden descent in the center of the furnace was greater than elsewhere.

It was also observed that the generally most reduced pellets came from sample points located close to or immediately above the tuyers. This was particularly notable in pellets from position 6 and tends to indicate that a proportion of the reducing gases “shortcut” upwards in the furnace from the tuyers. It was often observed that the reduction of pellets in such furnace positions occurred too quickly on the outside, leaving the pellet core unreduced, deep down in the furnace. The shortcutting of gases may be an effect of the relatively large size of the tuyers used during the first furnace campaign. Several modifications have been made to the experimental blast furnace after the first campaign. Tuyere diameters have been reduced and movable armors installed to improve the gas distribution.

CONCLUSIONS

Pellet samples from one dissection of an experimental blast furnace have been analyzed in order to provide information on the state of the furnace and the reduction properties of the pellets at various stages of reduction. Single pellets were characterized by assigning 12 different FeO/Fe structure types to observed zones within each pellet. These basic data, as well as coordinates of the samples, are collected in a carefully designed database.

To access the data and making them available to users, the following tools have been developed:

- a web-server that can extract data from the database
- a web-browser with integrated support for 3D-visualization.
- a visualization tool that can communicate both with the web-server and the web-browser.

It is demonstrated that this system enables the user to identify e.g. details on the reduction behavior of a certain type of pellet in the blast furnace. The system is designed to provide access to detailed data for the user while also retaining flexibility for further development.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge LKAB’s permission to publish this work. Helpful comments and suggestions from Professor Sverre E. Olsen are also gratefully acknowledged.

REFERENCES

APPENDIX 1

Optical micro-graphs of the FeO\textsubscript{y}/Fe structure types identified during the characterization of sample pellets, taken with a digital camera.
Structure Type 1 (ST1) – Coarse grained hematite. Hematite that cover several grains like “patches”. This type of hematite exists either in the pellet core or adjacent to “old” magnetite.

Structure Type 2 (ST2) (left) and ST3 (right)

ST2 – Middle coarse grained hematite. Larger size hematite but that covers only one grain. Often found as an intermediate layer between ST1 and ST3 or in the middle of a pellet not containing ST1.

ST3 – Fine-grained hematite. Small equiaxed hematite grains that generally are found in the outer region of a pellet or as an interface between coarser hematite and “new” ST6 magnetite.

Structure Type 4 (ST4) in ST1

ST4 – Hematite lamellae. Often found as thin needles in small old magnetite grains or as a “checkered” pattern in larger grains.

Structure Type 5 (ST5) – Larger separate magnetite grains. These grains generally exist in the middle of a pellet. Sometimes embedded in a light gray wustite matrix.
Structure Types 6 (ST6) – Mixed sized magnetite grains that can partly be “matrix-like”. A more dense structure than ST5. Often found as an outer layer over hematite or middle layer between hematite and wustite.

Structure Types 8 (ST8) in 7 (ST7) (Left) and ST7 in ST8 (Right)

ST7 – Magetite matrix – Continuous bulk of magnetite that is often partly reduced to wustite or in between hematite grains.

ST8 – Wustite. Continuous phase of non-separate grains. Appears light to dark gray after etching, depending on if there is residual magnetite in the wustite.

Structure Type 9 (ST9) – Metallic iron. Smallish “snowflake” crystal like grains. Appears white to light gray, also in polarized light. Can sometimes appear pink in polarized light due to surface oxidation (magnetcite), but still has very characteristic shape.

Structure Type 10 (ST10) – Old magnetite. Magnetite that has not been through complete oxidation during the pelletization. Magnetite is only categorized “old” if found inside a structure consisting of, or containing hematite. Looks in structure often like ST6.
**Structure type 11 (ST11)** – Metallic iron that has sintered together into a coarser "sponge-like" porous structure.

**Structure type 12 (ST12)** – Metallic iron that has melted together into a more solid structure with some pores.