THE USE OF AN EXPERIMENTAL BLAST FURNACE FOR RAW MATERIAL EVALUATION AND PROCESS SIMULATION

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Synopsis: The experimental blast furnace located at Mefos in Luleå, Northern Sweden was built and commissioned at the end of 1997. It was built and financed by the iron ore company LKAB, to serve as a tool for product development of iron ore pellets. During the last 2 ½ years six campaigns has been run successfully and the furnace has proven to be a very useful tool for realistic simulation of the blast furnace process. The paper describes the furnace, test procedures and some results from the six campaigns. Some results from two dissections of the quenched furnace are also presented. A discussion of the relevance and validity of the blast furnace results is made, together with results from comparisons of the experimental furnace and commercial size blast furnaces.

Keywords: blast furnace, experimental blast furnace, raw materials, iron ore pellet, dissection

1. Introduction

The need for a step in between laboratory scale metallurgical testing and full-scale tests of new blast furnace pellets has been more and more evident during the last 10-15 years. An experimental blast furnace is a way to reduce the risks before full-scale tests are performed. The possibilities for operating an experimental blast furnace in a broad range of process concepts can also allow for faster progress in pellet development and for testing concepts too risky to test directly in a full-scale blast furnace.

In 1994 a feasibility study was initiated to evaluate the possibilities to build and design an experimental blast furnace. This was done by Mefos (the metallurgical research foundation in Luleå, Sweden) and LKAB in co-operation and discussions were made with experts from all over the world. In October of 1996 the LKAB board of directors decided to build the furnace and also to run five campaigns in 1997-1999. Hot commissioning started in 1997 and in 1997-2000 six test campaigns were carried out.

The experimental blast furnace in Luleå is a strategic investment that enables faster, assured product development. The blast furnace is a cornerstone of LKAB's research and development efforts. By using an experimental blast furnace in the process of product development, LKAB expects to strengthen its position as a leading supplier of blast furnace pellets, in terms of product quality and performance. The goal is to design and produce pellets that create added value in the customer's process, compared to other burden materials.

The present blast furnace pellet of LKAB was first introduced in 1982. It is produced from magnetite ores, mined in Kiruna or Malmberget. The concentrate has a very low gangue content. Bentonite is added as a binder and olivine to adjust the composition before pellets are formed and fired. During almost twenty years, outstanding operational results have been achieved in Nordic blast furnaces, using 100% olivine pellets.

2. The experimental blast furnace

The experimental blast furnace was fully financed by LKAB, who also owns the furnace. It is situated at the Mefos premises, next to the Luleå plant of SSAB. During operation SSAB supplies a lot of the raw materials, including gases, and carries out analyses on hot metal and slag, etc. This has had a great influence on the costs of building and operating the experimental blast furnace. LKAB and Mefos are operating the blast furnace in co-operation.

2.1. Description of the furnace

The experimental blast furnace is shown in Figure 1. It has a working volume of 8.2 m³ and a hearth diameter of 1.2 m. From tuyere level to stock line the height is 6 m, and there are three tuyeres placed with 120 degrees separation. The tuyeres have a diameter of 54 mm, resulting in a blast velocity of 150 m/s at normal
blast volume. The furnace is equipped with systems for injecting pulverised coal, oil and other injection materials.

![Figure 1. Layout of the experimental blast furnace](image)

Great effort has been taken to keep heat losses to a minimum and therefore insulating refractories were chosen. Only the bosh and tuyeres are water-cooled. The blast is normally preheated to 1170-1250°C in pebble bed heaters. There are two pebble bed heaters, working in cycles.

The raw materials system consists of four bins for pellets or sinter, one bin for coke and two small bins for slag formers. Each material is weighed separately according to the actual recipe. The material is transported to the furnace top by a skip and to a receiving hopper. Below the receiving hopper, there is a pressure equalising lock hopper. Furnace top pressure can be controlled up to 150 kPa overpressure.

The experimental blast furnace is equipped with a bell top. There is a moveable armour for burden distribution control. Two mechanical stock rods are used to monitor the burden descent and to control the charging into the furnace. The top gas is transported through the uptakes and down-comer to a dust catcher. The gas is further cleaned in a venturi scrubber and a wet electrostatic precipitator. Finally, the top gas is flared in a torch.

The furnace has one tap hole. It is opened with a pneumatic drill. After each tap, the tap hole is closed with a hydraulic mud gun. The hot metal and the slag are tapped into a ladle, transported to the SSAB steel plant, and charged as scrap to the BOF.

Burden probes are installed at three different levels. There are two horizontal probes, one at tuyere level and one in the shaft, and one inclined probe to sample in the bosh. The shaft probe and the inclined probe are equipped with two different heads. One is used to collect material samples from the furnace, while the other is used to collect furnace gas for analysis; and to measure the temperature. The tuyere probe is equipped with a gas collecting and temperature-measuring head.

To make dissection and repair easy the hearth is detachable and can be separated from the furnace in one to two hours.

2.2. Raw Material preparation and dust treatment

The raw materials for the experimental blast furnace are normally produced before each campaign. The test pellets are produced either in the Steel Belt Plant located in Malmberget, or in one of the grate kiln plants located in the Kiruna area. Pellets are made using normal pellet feed concentrate. The balling and induration is done at standard plant practise, which means that the test pellets have normal size distribution.
Test pellets are transported to the experimental blast furnace and stored in a stock house. During the campaigns the pellets are screened at 6 mm and sampled before they are stored in day bins.

Sinter is transported from the actual steel plant to the stock house at the experimental furnace. It is normally standard sinter as produced at different steel plants. The sinter is sampled and tested in the same way as for the pellets.

Coke is produced at SSAB coke plant in Luleå, close to the blast furnace. Before each campaign production coke is screened in the fraction 15-30 mm. The coke is transported to the experimental blast furnace for storage in the stock house. During campaigns, coke is transported to the experimental blast furnace with a front loader, screened at 6 mm and sampled before storing in the day bin for coke.

Fluxes are screened to the fraction 10-20 mm and stored in big-bags. The big-bags are transported to the day bins, no additional screening of fines is done.

Dry flue dust is collected in a storage container, sampled twice a day and analysed for the chemical composition. The wet flue dust (sludge) is collected in a thickener and sampled when the thickener is emptied by a suction truck.

2.3. Operating the experimental blast furnace

The operation of the blast furnace is very similar to a commercial blast furnace. At blow-in a small amount of charcoal in front of the tuyeres is used as start up burden. Within the first hour, full wind is reached and the blast temperature is in the range of 800-850°C. The blast temperature is increased to the desired set point in the first 24 hours of operation. The amount of reducing agents is slowly decreased during the first 72 hours, to a level corresponding to about 110%, compared to normal operation. After this period injection of coal or oil is started. Operation is stabilised during the next 48 to 72 hours.

The furnace is operated at a productivity ranging from 3.4 to 4.0 t/m³day. Hot metal and slag composition is kept at set points decided before the campaign. Normal tap-to-tap time is 60-80 minutes, depending on actual production rate; and the normal tap duration is five to fifteen minutes. Drill diameter varies between 25 and 28 mm, depending on tapping conditions in previous tap. The hot metal temperature is measured with a temperature probe. Hot metal and slag are sampled and analysed after every tap.

The test periods normally starts with a transition period where the test material is charged to the furnace for a period of 24-36 hours, corresponding to six to nine throughputs. After that period the actual test starts. The test time depends on what objectives that are to be met for the test. A typical test period range from two days up to six days. During this time operational data is logged and monitored closely. Process data are logged every second and stored in a database, as ten-second and minute averages. These data are transferred at regular intervals to another database where process data calculations are carried out. Data in this database is used for reports, trend charts and mass- and heat balance calculations. Chemical analyses for raw materials, hot metal and slag are also stored in this database.

Reference material is charged to the furnace at regular intervals to check if there has been any change in the furnace or auxiliary equipment that influence the operation.

Sampling of burden materials, using the burden probes, is done once or twice every shift. The material retrieved by the probe is divided into samples representing different positions on the radius of the furnace. All material taken out of the furnace is screened and the fraction >6.3 mm is sorted, so that pellets, coke and slag formers are separated. Breakdown and strength of materials are tested and samples are prepared for microscopy investigations. Chemical analysis is also done, primarily to determine the overall reduction degree.

The efforts to keep heat losses to a minimum have proven sufficient. Because of this the consumption of reducing agents are similar to many full-scale blast furnaces. The chemical and thermal treatment the pellets undergo in the experimental blast furnace can therefor be said to simulate a full-scale blast furnace. As to now the experience is that the experimental blast furnace is a very sensitive tool for detecting differences in properties for different pellets. The response time is much shorter for the experimental furnace compared to a commercial furnace. One example is the time for the blast furnace to go from normal heat levels to cold conditions, it could take less than six hours. On the other hand, the blast furnace also recovers quickly to normal conditions, after corrective actions are made.
2.4. Campaigns 1 - 6

During the campaigns performed so far, many different process concepts have been tested in the experimental blast furnace. Examples are:

- 100 % pellets as ferrous burden with injection of PCI in the range of 0 – 150 kg/tHM.
- Simultaneous injection of PCI/slag formers and oil injection up to 65 kg/tHM. The slag rate has varied between 85 kg/tHM and 190 kg/tHM.
- Sinter/pellets as ferrous burden with pellet ratio from 20 % to 60 %. Oil injection up to 65 kg/tHM. Slag rates between 170 kg/tHM to 220 kg/tHM.

These various operation modes have given different results not only in consumption figures but also in process characteristics. For example, it is interesting to see the difference between 100 % pellet operation and operation with high amounts of sinter. The big difference is in the rate of change in operating condition, meaning that when operating with high amounts of sinter a slower response in the operational parameters can be seen, when changes are made. This is probably due to harder burden structures (less moveability) in the case of sinter burdens.

3. Test procedures and results from iron ore pellet evaluations

The blast furnace process is, as well known, complex. Although the fundamentals are the same for all operations, even two different blast furnaces at the same plant behave differently. This means that the evaluation of actual operation data with the goal to rank different raw materials and their associated properties is difficult. In general, there is an agreement of the paramount importance of raw materials quality to blast furnace operation results. Some estimates have been made that 80% of the overall result is dependent of the raw materials used. This is true, not only for the quality of the ferrous burden components, but also for coke, fluxes and injection materials such as pulverised coal.

The issue about ranking different pellets, e.g. what are the characteristics of a good pellet, have been under discussion during many years. When it comes to judge and discriminate between different pellets tested in the experimental blast furnace, the following criteria are used:

1. The overall permeability and its variation during operation, measured as the Burden Resistance Index (BRI). This index is calculated based on the pressure drop from tuyere level to top and the bosh gas volume ((blast pressure^2-top pressure^2)/(bosh gas volume)^1.7 * k_i).
2. The gas utilisation and its stability, measured as \( \text{\%CO} / (\%CO + \%CO_2) \), calculated from top gas analysis.
3. The burden descent rate, and its stability, calculated from stock rod information.

4. Results from dissections

After each experimental blast furnace campaign the blast furnace has been quenched and dissected. When furnace operation is shut down, nitrogen is flushed from the furnace top down through the blast furnace burden. This action prevents a heat wave moving upwards through the furnace, and causes the blast furnace reduction to “freeze”, i.e. stopping all further chemical reactions. After two to three weeks of cooling down the burden by nitrogen the furnace top is removed and dissection can commence. Dissections are carried out by carefully removing the burden material layer by layer, starting from the top of the blast furnace. As long as possible, the original pellet and coke layers are followed. The work is concentrated on the pellet layers.

The appearance and nature of each burden layer uncovered is documented in the form of photographs and video shots. After that material samples are taken from several points of the burden surface, for chemical analysis, physical testing and microscopic characterisation. Figure 2 shows an example of the development in reduction degree in samples taken out at one specific point in each ferrous burden layer down through the furnace, while Figure 3 shows the microscopic structures observed at the same sample point.
Figure 2. Development in reduction degree in each ferrous burden layer down through the furnace.

Figure 3. Example of microscopic structures at the same sample point as in Figure 2 above.
Figure 2 and 3 above are from dissection after Campaign 1, where the blast furnace was charged with an olivine iron ore pellet, MPBO, table 1. In Figures 4 and 5 below, a comparison of differences in reduction disintegration between two pellet types and at different locations in the furnace is made. Figures 4.A and B are from Campaign 1 while Figures 5.A and B are from Campaign 4, where the furnace burden was a fluxed pellet, FP20, table 1. The A samples are taken out close to the furnace wall, while the B samples are from the furnace centre. The per cent of reduction disintegration is calculated from screening results after mechanical tumbling of the samples. The reduction disintegration is divided into two groups, <0.5 mm and 0.5-6.3 mm.

Table 1. Compositions of pellets in the dissections after Campaign 1 and 4 respectively.

<table>
<thead>
<tr>
<th>Pellet</th>
<th>Type</th>
<th>Fe (%)</th>
<th>SiO$_2$ (%)</th>
<th>CaO (%)</th>
<th>MgO (%)</th>
<th>Dissection</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPBO</td>
<td>Olivine</td>
<td>66.8</td>
<td>2.0</td>
<td>0.4</td>
<td>1.5</td>
<td>Campaign 1</td>
</tr>
<tr>
<td>FP20</td>
<td>Fluxed</td>
<td>66.9</td>
<td>1.6</td>
<td>1.6</td>
<td>0.3</td>
<td>Campaign 4</td>
</tr>
</tbody>
</table>

From Figures 4 and 5 it can be seen that the reduction disintegration into 0.5-6.3 mm is in the beginning larger for the fluxed pellet, while further down the blast furnace shaft the olivine pellet has the higher values. A critical point is observed, especially for the fluxed pellet, where the reduction disintegration has a maximum and then decreases further down in the furnace. The dust formation, <0.5 mm, on the other hand, has a tendency of increasing down through the furnace.
Before quenching the blast furnace several basket samples are introduced into the burden layers. The individual baskets contain about 600 grams of raw material, and provide the opportunity to study the behaviour of several different burden materials after each dissection. The material from each basket sample is also examined chemically, physically and by microscope; and is compared to the “bulk” material next to the individual baskets.

To be able to evaluate and present the vast amount of data that is produced during the dissections a visualisation model has been developed, displaying data in a three dimensional mode.

5. Results from simulation of a commercial blast furnace

Some burden mixtures tested in LKAB’s experimental blast furnace have been tested also in commercial blast furnaces. In table 2 an example of a burden mixture tested at the steel plant Stahlwerke Bremen in Germany is shown. The no 2 blast furnace in Bremen has a diameter of 12 m, and is charged with a mixture of sinter and pellets (together with a small addition of lump ore).

<table>
<thead>
<tr>
<th>Experimental blast furnace</th>
<th>Bremen no 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burden A</td>
<td>Burden B</td>
</tr>
<tr>
<td>?CO (%)</td>
<td>45.7</td>
</tr>
<tr>
<td>Std dev, ?CO</td>
<td>2.9</td>
</tr>
<tr>
<td>Permeability resistance, BRI</td>
<td>6.6</td>
</tr>
<tr>
<td>Std dev, BRI</td>
<td>0.25</td>
</tr>
<tr>
<td>Burden A</td>
<td>Burden B</td>
</tr>
<tr>
<td>?CO (%)</td>
<td>47.2</td>
</tr>
<tr>
<td>Std dev, ?CO</td>
<td>0.7</td>
</tr>
<tr>
<td>Permeability resistance, BRI</td>
<td>6.7</td>
</tr>
<tr>
<td>Std dev, BRI</td>
<td>0.17</td>
</tr>
<tr>
<td>Burden A</td>
<td>Burden B</td>
</tr>
<tr>
<td>?CO (%)</td>
<td>48.1</td>
</tr>
<tr>
<td>Std dev, ?CO</td>
<td>2.4</td>
</tr>
<tr>
<td>Permeability resistance, BRI</td>
<td>6.7</td>
</tr>
<tr>
<td>Std dev, BRI</td>
<td>0.81</td>
</tr>
<tr>
<td>Burden B</td>
<td>Burden B</td>
</tr>
<tr>
<td>?CO (%)</td>
<td>48.6</td>
</tr>
<tr>
<td>Std dev, ?CO</td>
<td>2.1</td>
</tr>
<tr>
<td>Permeability resistance, BRI</td>
<td>6.7</td>
</tr>
<tr>
<td>Std dev, BRI</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Burden A is a mixture of 54% sinter, 23% fluxed pellet and 23% olivine pellet, while in burden B the olivine pellet is changed to an acid pellet. This example shows that even a small change of the blast furnace burden (23% in this case) alters the behaviour of the furnace operation. The results from the experimental blast furnace show how the burden will behave in a commercial blast furnace.

6. Conclusions

The experimental blast furnace is a unique test facility for blast furnace burden materials. It gives big opportunities for product development and process research. Many of the risks involved in full-scale production trials can be avoided. The furnace was primarily built for the purpose of product development, but is also used in other blast furnace related research projects.

As burden material can be sampled from the furnace during operation or after quenching, investigation of reduction mechanisms for various materials and process conditions can be done. This will aid future design of blast furnace pellets.

Several dissections of the experimental blast furnace have provided many interesting research results. The change in properties during reduction in a blast furnace can be studied in detail. An example is the reduction disintegration, which has been found to vary between different pellet types as well as along the radius and height of the furnace.

Results from the experimental blast furnace have been verified by full-scale trials in the Bremen no 2 furnace. This shows that results from the experimental blast furnace can predict how a burden material, or burden mixture, will behave in a commercial blast furnace. Possible effects of inferior raw material quality are more pronounced in the experimental furnace compared to when the same raw material is tested in a full-scale blast furnace.

Used to its full potential, the experimental blast furnace will serve as a valuable tool for blast furnace development and to improve process efficiency. The experimental blast furnace strengthens Luleå’s position as an internationally significant centre of metallurgical development.