Ten years of experimental blast furnace research

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Abstract

LKABs Experimental Blast Furnace (EBF) in Luleå, Sweden was first commissioned in 1997. During the years it has been in operation, 21 different test campaigns have been done. Many different aspects of the blast furnace process have been analyzed and tested during these campaigns. Such testing includes, for example, testing of injection techniques with coal-flux co-injection, high oxygen/oil injection, blast conditions testing with high moisture, investigations of scaffolding, evaluation of equipment and measurement devices. This paper describes the history of the research activities, using the EBF as a tool in blast furnace process evaluation.

The EBF itself has improved in instrumentation, burdening, injection and probing equipment. One of the major improvements, has been the development of a test methodology that assures the scientific results from tests and experiments. In all, 17 dissections have been done after quenching the EBF, at the end of campaigns. At these many hundred of basket samples have been collected, together with burden samples.

The tests have been addressing different topics like strategies for the raw material mix, the blast parameters settings, the hot metal quality, detecting conditions that can cause disturbances in the operation and so on. Results have helped to better understand how the physical parameters and chemical composition of the materials determines the softening/melting behaviour and slag composition and the resulting operation performance. It has also helped to find correlations between process parameters and blast furnace operation. The evaluation of samples from the different dissections have also given information about degradation of raw materials, alkali uptake, carburization and the formation of iron and slag.

Introduction

During the 60s and 70s several experimental blast furnaces were in operation. In those days, much new knowledge were found and the blast furnace operation results were improved in terms of energy efficiency and productivity.

During the 80s and 90s LKAB developed a strategy to focus on iron ore pellet production that resulted in building a new pelletizing plant in Kiruna and reopening of the Svappavaara pelletizing plant.

The product development of iron ore pellets was intensified as new drivers for blast furnace operation started to evolve. Among these were the increasing amounts of oil or pulverised coal, high oxygen enrichment and recycling of secondary materials [4]. The main result for blast furnace operations were increased productivity and higher demands on quality parameters of iron ore products and coke.
The possibilities to use full scale trials at customer as a tool was limited by the potential high risks involved and because these trials often are non-conclusive. There was also the fact that laboratory testing is not sufficient to predict blast furnace process behaviour.

As a result of these factors, LKAB’s experimental blast furnace in Luleå (EBF) was built and commissioned in late 1997, primarily for product development of iron ore pellets. The target for the design and construction of the (EBF) was to create a small blast furnace where the burden was subjected to conditions similar enough to full scale furnaces to obtain realistic testing. At the same time to improve knowledge about the blast furnace process to increase the understanding of LKABs customers needs. Within the first few campaigns it became clear that the EBF was a very valuable tool not only for development of pellets but for other research and development of the blast furnace process.

In the period 1998 to 2008 twenty-one campaigns were completed. After seventeen of the campaigns, the EBF was quenched using nitrogen and dissected. The EBF has been described in detail in other papers [1],[2], [6] below is a summary of the plant and operation characteristics.

The EBF plant is shown in Figure 1. It has a working volume of 8.2 m$^3$ and a diameter of 1.2 m at tuyere level. The working height from stock line to tuyere level, is 6 m and there are three tuyeres placed with 120 degrees separation, each with a diameter of 54 mm, resulting in a blast velocity of about 150 m/s at normal blast volume. The furnace is equipped with systems for injecting pulverised coal, oil, gas and other materials.

The blast is normally preheated to 1150°C - 1250°C in pebble bed heaters. The raw materials system consists of four bins for pellets or sinter, one bin for coke and four small bins for slag formers. The materials are transported to the furnace top by a skip to a receiving hopper. Furnace top pressure can be controlled up to 150 kPa overpressure.

The EBF has a bell-less top. The top gas is cleaned in a conventional gas cleaning system. Finally, the top gas is flared in a torch. The furnace has one tap hole. It is opened with a pneumatic drill. Burden probes are installed at three different levels. There are two horizontal probes, one at upper shaft, and one at the lower shaft. The third is an inclined probe at the
bosh level. The shaft probes and the inclined probe are equipped for sampling materials and for measuring furnace gas analysis/temperature, during operation. Vertical probing is also done during the campaigns. In 2007 the EBF plant was connected to a VPSA plant for CO\textsubscript{2} removal. This combination made it possible to test top gas recycling.

All burden materials are screened at 6 mm and sampled before stored in day bins. Sinter and lump ore has a top size of 50 mm. Iron ore pellets are normal industrial size. The coke is prepared by screening to the fraction 15 – 30 mm. A batch for a whole campaign is prepared and transported to the EBF. Fluxes are screened to the fraction 10 – 20 mm.

**Operating the experimental blast furnace**

The operation of the blast furnace is very similar to a commercial blast furnace. After blow in, the furnace is operated with a productivity ranging from 3.4 to 4.7 t/m\textsuperscript{3}day. Hot metal and slag composition is kept at set points decided before the campaign. The tap-to-tap time is 60-80 minutes. The hot metal temperature is measured and hot metal and slag are sampled at every tap and analysed. A typical test period range from two days up to six days. During this time operational data are logged and monitored closely. Sampling of burden materials, using the burden probes, is done once or twice every shift. Probing to measure the temperature profile and the gas composition are also made at regular intervals. Process data are logged and stored in a database. Chemical analyses for raw materials, hot metal and slag are also stored in this database.

Data are used for reports, trend charts and mass- and heat balance calculations. It has been shown that the EBF is capable of simulating the operation of commercial furnaces well [5]. It has also proven to be a sensitive tool for detecting differences in properties for different ferrous burden materials. The response time is shorter for the EBF compared to a commercial blast furnace.

At the end of the different campaigns the EBF is quenched and dissected. During the final hours of operation basket-samples with various test materials are introduced into the furnace. At shut-down the burden column is flushed with nitrogen gas from the top and the reduction reactions stops. The furnace is cooled for about fourteen days before dissection starts.

Dissection is done like an archaeological excavation. As long as possible, the original pellet and coke layers are followed. Samples are taken from every layer, according to a predetermined plan. Small samples for microanalysis are collected as well as larger samples for chemical and mechanical testing, sometimes whole structures are preserved, like parts of the cohesive zone or parts of the raceway.

![Temperature profile in the experimental blast furnace](image)
The dissections are documented by photographs and video filming, in addition to written documentation.

The zones that normally are present in full-scale blast furnaces should also exist in the EBF. This is important for correct simulation of a full-scale blast furnace. In Fig 2 the results from an vertical probing are plotted. The graph shows the presence of the drying zone, the reserve zone and the start of the cohesive zone, given by the temperature gradient in the EBF.

In all dissections, there has been a distinct cohesive zone, located about 1 - 1.5 meters above tuyere level, different in shape, width and position depending on process conditions and the raw materials used [8].

**Experimental design for EBF trials**

In the first campaigns much attention was put on the performance of different iron ore pellets and their interactions with iron ore sinter and lump ore. Key parameters were process stability, gas utilisation, consumption of reductants and hot metal quality. These parameters were important for evaluating different pellet compositions and the associated process results. Most of the time the process settings were more or less constant. This method was sufficient for predicting the iron ore pellet performance in full scale blast furnaces [1], [2].

Later when various process conditions and more complex raw materials schemes were tested a more elaborated test design was required. This also meant that the evaluation of the test results could be improved [4]. Today experimental design have been introduced and evaluation is done with the help of multivariate methods. There are however still a lot of work to characterise the materials sampled from the EBF. One help in that respect is the newly installed Qemscan equipment that we hope will increase the capacity for quantitative characterisation of micro samples.

**Overview of the campaigns**

During the 21 campaigns performed so far, many different process concepts and more than 40 different ferrous burden materials have been tested in the EBF. The major research areas that has been addressed during the campaigns are:

1. Iron ore pellet development, including coating with different minerals.
2. Raw materials interactions in mixed burdens.
3. Coke properties and interaction with ferrous burden materials.
4. Pre-reduced ferrous burden in the blast furnace
5. Injection of reductants, slag formers and recycled materials
6. Operation at low slag volumes.
7. Top gas recycling with CO2 capture

The main objectives in all these tests were to improve the BF operation in one or several of the following aspects:
- Lower specific energy consumption.
- More efficient use of raw materials
- Higher specific productivity
- Provide a consistent hot metal composition with small variations
- Stability of the operation
Calibration of the EBF

In campaign 1 the main objective was to test the function of the EBF plant. After two weeks of operation the plant was rebuilt and the campaign was restarted. A “calibration” test to compare operation results with the SSAB blast furnace No. 2 in Luleå was done. The main results from this test were:
- Higher silicon level in the hot metal, about 1% higher
- Higher coke rate 520 kg/thm vs. 465 kg/thm in the full scale operation a difference of 55 kg/thm

The difference in coke rate can be explained by higher heat loss in the EBF and higher silicon level in the hot metal. Theoretically the increased silicon level corresponds to about 45 kg/thm.

Iron ore pellet development, including coating with different minerals

The quality of raw materials is the most important factor for blast furnace operation results. 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 ferrous burden undergoes a number of chemical and physical transitions during its processing in the blast furnace. Because of the nature of the process one of the most important properties of the ferrous agglomerates is to withstand these transitions without deformation or degradation. Once in the area of the cohesive zone the reduced agglomerates should rapidly transform into liquid phase with good fluid properties assure a good drainage from the cohesive zone through the dead man to the tap hole area.

The results from the EBF tests with different pellets, has led to the development of new pellet compositions [9]. One is designed for 100% pellet operation and one for mixing with high basicity sinter. The pellet developed for sinter burdens gives good primary slag properties for the mixed burden [7].

One important observation from the different dissections are the large structures that can be seen in the burden. These can hinder or even stop the normal descent of the burden. This phenomena is probably common in blast furnaces and explains the presence of operational disturbances such as hangings, slips and variations in heat level. They are formed when one area of a ferrous burden layer is “welded” together in the contact points where newly reduced iron forms. The number of these welded masses seems to increases with higher reducibility if the ferrous burden materials [10]. This phenomena is the reason for the different tests with coating with various minerals on blast furnace pellets [12].

Raw materials interactions in mixed burdens.

The slag phase has a strong interaction with the iron oxides in the pellet during reduction and several slag phases containing iron are formed [4]. The composition of the slag phase and the melting point determines much of the pellet behaviour during reduction [10]. The reducibility of the pellet is also linked to the different phases of the slag. When combining several different types of iron ore agglomerates the primary slag formation for the combination has to
be considered. It is important to “match” the individual ferrous burden materials with each other. Lump ore is an attractive burden material in many operations. The main drawback is that the composition and mineralogical structures seldom are homogenous. This means that large differences in reduction properties and reduction strength can be expected. The experience from test in the EBF is that larger amounts of lump ore, more than 15-20 % of the burden gives significant higher coke rates and unstable operation [13].

**Prereduced burden**

The concept of pre-reduced burden has been used for many years. Metallized materials like scrap, DRI and HBI has been used for lowering the coke consumption and to boost productivity.

In the ULCOS project the concept was used to see how much effect a partly metallized burden would have on the coke rate and thereby lowering the CO$_2$ generation from the blast furnace. The test was made with a burden of about 60% metallization and the results showed a decrease in coke rate by more than 50 %. During the trial the process was extremely stable.

**Injection techniques of reductants, slag formers and iron- and coal-containing materials**

Injection of reducing agents such as Pulverised Coal (PC), oil and Natural Gas (NG) are more or less a standard for most of blast furnace operations world wide. The driving force is the possibility to reduce the coke consumption, but also to get a reduction gas with higher amount of hydrogen. The later aspect is important in the case of variations in reduction behaviour of the ferrous burden to help to create a more stable blast furnace operation.

In the EBF pulverised coal (PC), oil and gas have been used. The experience is that gas injection is the most efficient way to decrease the coke rate, followed by oil injection and PC injection (PCI). The most important factor for successful injection is to make sure that a good combustion is achieved, this is probably the reason for the efficiency in gas injection. At the EBF the use of co-axial lances equipped with swirl tip made a very big difference in possible injection rates both for coal and oil [14].

Tests with co-injection of PC/BOF slag and PC/flue dust was done in the EBF [15], [17]. The main objectives for these tests were:
1. To improve the slag formation in the blast furnace by avoiding high viscosity slag to be formed in the cohesive zone
2. To improve slag formation in the raceway area and the drainage of slag down to the hearth
3. To recycle dust and slag containing iron and coal

The ferrous burden consisted of 100 % pellets. Good blast furnace performance was achieved during the trial, with smooth and stable operation. The total slag volume (final slag) was around 100 kg/tHM and the reductant rate was lowered by 11 kg/tHM, compared to the reference period. A significant stabilisation and reduction in hot metal silicon content was reached, as well as an improved sulphur distribution. The injection rate was 100 kg/tHM PC and 36 kg/tHM BOF slag. Quenching and excavation of the EBF showed that the formation of a birds nest could be avoided when the acid slag, normally generated in the race way, is fluxed with BOF slag [16]. Injection of BOF slag opens up new opportunities to further develop the blast furnace process.
The trials with co-injection of BF flue dust and PC resulted in a decrease in coke rate corresponding to 1.5 times the amount of carbon in the flue dust, mostly because a significant reduction in hot metal silicon content. The flue dust injection rate was 23 kg/tHM.

**Operation at low slag volumes.**

In Sweden and Finland blast furnace operation with low slag volumes is standard practise since many years. It is the possibility to get high iron content in the pellets and sinter that have promoted this development. In order to find out the lowest practical slag volume a trial was made with slag volumes below 130 kg/tHM. The results shows that substantial benefits can be achieved when the slag volume is decreased. The main obstacle is when the slag is used for other products, in these case the high sulphur and high MgO content can lower the quality of these products.

**Top gas recycling with CO2 capture**

One of the main technologies for low CO\textsubscript{2} iron making in the ULCOS project is the concept of the Top Gas Recycling Blast Furnace, TGRBF. The EBF was equipped with a CO\textsubscript{2} separation unit installed by Air Liquid based on the VPSA technology. During a 5 week trial, different configurations of the concept was tested and a dramatic decrease in coke consumption was achieved.

**Observations from some of the different dissections**

The main outputs from each dissection are:
- position, shape and characteristics of each individual coke and ferrous burden layer in the EBF
- assays of ferrous burden materials
- mechanical strength of ferrous burden materials
- structure and phases present in individual iron ore pellets sampled in the furnace.
- analysis of “interesting” anomalies in the furnace, such as scaffolds, dusts, agglomerates and so on.

By combining these outputs it is possible to characterise the overall properties of the burden column as found in each dissection of the EBF.

All dissections show the presence of channels and cavities in the burden column. These are generally located at the furnace wall, but in some cases they are found in the centre or near centre of the furnace. The cavity or channel located in the centre or near the centre at the lower shaft of the furnace that was
found in all dissections, is most likely the space where loosed packed coke has been flowing to the tuyeres.
In Figure 3 an example of the macrostructure of the burden is given. In this case the cohesive zone (CZ) is in the shape of a inverted V.

Some other results from the various dissections made in the EBF are [8], [10]:

1. Despite differences in reducibility as measured in laboratory tests for different burden materials the reduction degree for respective material sampled at the same level in the furnace are nearly the same
2. The alkali (K, Na) is concentrated in the ferrous burden near to the cohesive zone
3. The zinc accumulates in the upper/middle shaft
4. The pick up of sulphur corresponds to the amount of CaO in the ferrous burden materials.

Other observations that are consistent for the different dissections are the presence of not melted slag formers all the way down to the tuyere level. Burden flux material like limestone and quartzite remain as discrete particles or as discrete masses (limestone after calcinations) because of their relatively high melting points.

Conclusions

A great deal of information has been gathered, new pellet compositions have been developed and the use of the EBF has been extended to include much more research than was originally planned. In addition, the furnace has been used extensively for applied research by LKAB, by LKAB’s customers, universities, various research organisations and other companies. The furnace is providing an excellent springboard to both the next generation of blast furnace pellets and blast furnace operations in the years to come.

List of symbols

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>CZ</td>
<td>The Cohesive Zone</td>
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<tr>
<td>Root</td>
<td>Part of the cohesive zone in contact with the blast furnace wall</td>
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<tr>
<td>dS-T</td>
<td>Distance from stockline to the top of the cohesive zone</td>
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<tr>
<td>dT-Re</td>
<td>Distance from the top to the end of the root of the cohesive zone</td>
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<tr>
<td>dT-Rs</td>
<td>Distance from the top of the cohesive zone to the start of the root</td>
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References


