Characterization of the State of LKAB Experimental BF Hearth

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INTRODUCTION

The state of the BF hearth is normally analyzed by indirect methods as evaluation of measured data as the opportunities to study the internal conditions of deadman and BF hearth in an industrial furnace is limited to once every 15-20 years. The time available to empty the hearth and take samples is normally limited due to a tight schedule for restoration of the blast furnace. The number of opportunities for verification of hearth models for thermal flow describing accretion and wear becomes few.

Since 1997 until 2009 the LKAB experimental BF (EBF) has been operated in two campaigns almost every year and after most of these campaigns it has been quenched and excavated. At the end of each excavation the hearth is detached and are available for studies on the hearth in terms of e.g. deadman conditions, accretion and wear. This provides unique opportunities to take samples from the coke bed in the hearth and study the distribution of material and changes in coke that has occurred in the blast furnace.

In this project the solid sampling is one tool for development and verification of a CFD model describing the hot metal and thermal flow in the hearth. The hearth conditions is examined relative operation conditions at the end of the campaign. A method for taking core samples and evaluating these has been developed in order get defined sub-sample positions along the depth of the hearth. Particle size distribution, bulk density and shape of solidified material are analyzed as well as the changes in chemical compositions of metal, slag, fines and coke. The results from the studies are concluded and discussed describing the hearth conditions and liquid flow relative position in the hearth.

THE LKAB EXPERIMENTAL BF

A schematic layout of the LKAB experimental BF plant is shown in Figure 1. From the erection of the EBF in 1997 until the fall 2009 23 campaigns with various types of trials have been carried out. Operational behavior and process results has been analyzed for various types of pellet burden separately or mixed with sinter, lump ore, and cold bonded pellet made from in-plant fines. The effect of injection trials with different types of coals, oil, gas, additives and titanium bearing materials have been carried out and the blast conditions varied. Reduction of CO₂ emission from the BF production has been studied in trials with charging of more or less pre-reduced burden and by recycling of top gas after CO₂ adsorption in VPSA equipment. As understood the EBF offers great opportunities to study conventional, modified or new process concepts for BF operation. The EBF can be modified and adapted to desired operational conditions for at trial.

Figure 1 The LKAB EBF plant
After most campaigns the EBF is quenched with N\textsubscript{2} from the top and after a couple of weeks cooling the excavation can start. The samples evaluated in this paper have been collected from the EBF hearth after dissection of the furnace down to tuyere level. The hearth is detached from the shaft and cores can be drilled down into the coke bed.

To operate the EBF is quite similar as to operate an industrial furnace in terms of process control system and automation but the response time after change is shorter. The raw material handling system consists of 4 pellets bins, one coke bin and four hoppers for additives. Weighed material is transported to the bell less top that distributes the material as desired. One mechanical stock rod is monitoring the burden descent and controlling the charging of the furnace. The EBF has a working volume of 8.2 m\textsuperscript{3} and a diameter at tuyere level and hearth level are 1.2 m and 1.4 m, respectively. There are three tuyeres placed with 120° separation. Great efforts have been taken to keep heat losses to a minimum and therefore insulating refractories were chosen. Only the bosh area and the tuyeres are water-cooled. The blast is normally preheated to 1200 °C in a new type of pebble heaters and can be enriched with O\textsubscript{2}. Gas, oil or PC can be injected with O\textsubscript{2} addition to the lance. The furnace is operated with an excess top pressure up to 1.5 barg. The furnace has one tap hole, which is opened with a drill and closed with a mud gun. The hot metal and slag is tapped together into a sand filled box.

The EBF hearth has three layers of insulating ceramic material and no bottom cooling to minimize heat losses and freezing of hot metal and slag. Thermocouples installed in the hearth are distributed in two rows with four thermocouples each in the positions 55°, 145°, 235° and 325°. The thermocouples are installed ~ 163 and ~ 213 mm in the ceramics at 10.97 m and 10.20 m levels, respectively. Two thermocouples are installed in the bottom of the EBF ~ 360 and ~ 260 mm in the ceramic lining.

**HEARTH CONDITIONS PRIOR QUENCHING**

The hearth conditions prior quenching are analyzed using thermocouple readings in the hearth, heat level in the EBF and tap data. The variation of hot metal temperature and bottom temperatures correlates quite well as shown in Figure 2. A period of lower hot metal temperatures results in lower bottom temperatures with some time delay. The bottom temperature and the hot metal temperature are higher prior the 2\textsuperscript{nd} quenching and core drilling. Hearth thermocouple readings show in general good correlation with hot metal temperature.

![Figure 2 HM temperature and bottom thermocouple readings during 1\textsuperscript{st} and 2\textsuperscript{nd} campaigns analyzed](image)

The upper row of thermocouples, at the position 10.97 m, shows in general higher temperatures and a greater variation around the blast furnace hearth compared to those at the position 10.20 m. The upper thermocouple at 55° shows highest short term variation during the 1\textsuperscript{st} evaluated campaign. The measured temperatures for the last week prior quenching are shown in Figure 3.

![Figure 3 HM temperature and temperature readings of 55° thermocouple at 10.97 m during the last week of operation before 1\textsuperscript{st} and 2\textsuperscript{nd} core drilling campaigns](image)
Except for the thermocouple readings also the HM C content is higher during the last week of 2nd drilling campaign with similar level of slag basicity. The C content of HM versus temperature is shown in Figure 4.

![Figure 4](image)

**Figure 4** C versus HM temperature prior quenching and core drilling

**CORE DRILLING INTO EBF HEARTH**

During four drilling campaigns six cores were drilled out in two layers on the diameter from tuyere no. 3 to the taphole as shown in Figure 5. Two drilling campaigns, hereafter named 1st and 2nd drilling campaign, were examined in more detail and photos of cores from these two campaigns are shown in Figure 5. Big lumps of taphole clay in the lower core close to the taphole at the 1st drilling campaign can be seen in the photos. Also in the lowest part of upper core some lumps were found.

During drilling material in the cores are compressed and the void fraction in drilled cores do not reflect the true void fraction of the coke bed. Cores with initially quite high void fraction gets more compressed compared to cores with a low void fraction.

![Figure 5](image)

**Figure 5** Position of drilled core samples and drilled cores are shown for two drilling campaigns. The photos of the cores are arranged similarly as the schematic figure of the hearth, 1st campaign to the left and 2nd to the right.
CHARACTERIZATION OF DRILLED CORES

Characterization Methods
Each of the drilled cores was divided into sub-samples of 10 cm length. The sub-samples were screened into fractions using 16 mm, 10 mm, 5 mm, 2.8 mm, 1 mm and 0.5 mm screens. Particles in fraction > 5 mm were manually separated in coke, magnetic material (mainly metal) and slag while the fractions 5-2.8 mm and 2.8-1 mm went through magnetic separation. The raw bulk density based only on material weight of each sub sample and the adjusted bulk density excluding magnetic material and slag > 5 mm were calculated.

The chemical compositions of 5-10 mm fraction of magnetic material, coke, and slag were analyzed as well as the < 0.5 mm fines fraction using XRF analyses. The magnetic fraction from the 1st drilling campaign could not be analyzed due to sample preparation problems indicating low C content of the material.

Graphitization degree of coke increases with the temperature coke has been heated up to. The graphitization degree is represented by the average crystallite height of coke carbon (L_c) was analyzed using XRD and Scherrer’s equation. L_c is calculated from equation (1) using XRD measurements at the (002) carbon peak position.

\[ L_c = \frac{0.89\lambda}{\beta \cos \theta} \]  

In the formula \( \lambda \) corresponds to the wavelength of the X-ray source, \( \beta \) is the FWHM (Full Width at Half Maximum) of the 002 carbon peak and \( \theta \) is the position of the 002 carbon peak. The 002 carbon peak has been corrected manually for contribution from an adjacent peak.

Characterization Results

Particle size distribution, bulk density and presence of coke, magnetic material and slag

![Graph showing particle size distribution](image)

Figure 6 Particle size distribution of each core drilled from EBF hearth 1st and 2nd drilling campaign

Figure 6 shows the average particle size distribution stated for each core. As shown in Figure 7, high ratio of magnetic material and/or fines contributes to a high raw bulk density. The ratio of coke > 5 mm is comparable low in the cores beneath the raceway and at the same time the ratio of magnetic material in > 5 mm fraction is quite large. This contributes to a high raw bulk density.

![Graph showing bulk density and presence of coke](image)

Figure 7 Coke, slag and magnetic material in > 5 mm fractions, fines < 1 and 2.8 mm and raw bulk density.
Figure 8 shows the adjusted bulk density with magnetic and slag > 5 mm excluded from the weight assuming that there is a void in which the melt can flow if the particles are greater than 5 mm. The adjusted bulk density is affected by the particle size distribution of coke, fine fractions, the ratio of magnetic material in fractions < 5 mm and presence of taphole clay. In drilled cores from 1st drilling campaign taphole clay filled the whole lower core from taphole position and therefore the bulk density of this core is high. No signs of taphole clay could be seen during 2nd core drilling, instead coke was present. After the excavation of the hearth the 1st drilling campaign wear could be seen close to the taphole.

![Adjusted Bulk Density kg/dm³](Figure 8)

The ratio of magnetic material is in the upper level of hearth highest beneath the raceways as shown in Figure 9. When moving downwards in the bed, the ratio of magnetic material decreases at the raceway position. However, the ratio is still higher or at the same level as at other positions. A great difference between the ratio of > 5 mm and > 1 mm as shown in the diagrams means that a considerable ratio of magnetic material in fraction 1-5 mm is present.

![Ratio of magnetic material > 5 mm and > 1 mm as function of depth in EBF hearth (1st drilling left, 2nd right).](Figure 9)

The shapes of magnetic material and slag are influenced by the void size and distribution in the bed. As can be seen from Figure 10 the drops has a straggling shape in volumes with high bulk density while the drops are round when the bed is more porous.

![Drops of metal 5-10 mm from regions beneath the raceways (left) and close to the taphole (right).](Figure 10)

Chemical composition of 5-10 mm coke fraction

The coke samples on which Lc values were estimated were sent for analyzes of chemical composition. For the second drilling campaign more or less all coke samples in 5-10 mm fraction were analyzed. The development of changes in coke composition is similar for both core drilling campaigns. The sum of oxides and alkali content in coke increase when moving downwards in hearth. The ratio SiO₂/Al₂O₃ also increases similarly.
Chemical composition of 5-10 mm magnetic fraction

Samples from both campaigns were sent for analyses but the magnetic material from the 1\textsuperscript{st} drilling campaign could not be prepared for analyses. This could be due to low C content. The Si content of metal analyzed can be seen in Figure 12. At raceway position the Si content is highest in the upper part and for the centre the result is opposite.

Chemical composition of 5-10 mm slag fraction

Basicities B2 and B4 of slag samples are shown in Figure 13. The chemical analyses of slag shows that slag basicity B2 close to the taphole in the upper core is quite close to the tapped slag while the slag in the upper core beneath the raceway has significantly higher basicity B2. The tapped slag basicity B2 was in average for the last three taps before quenching 0.93 and 0.90, respectively for the 1\textsuperscript{st} and 2\textsuperscript{nd} drilling campaign. Considering the basicity B4 the difference between samples are much less. The alkali content of slag is highest in the lower parts of the hearth and MnO is also slightly higher as shown in Figure 14. The S content of the slag correlates in general to the basicity of the slag and the major part of samples has S content of 1.5-2 % of S. This is higher than in the lasts taps for the campaigns with slag containing 1.2 and 1.4% of S, respectively.
Figure 14 Content of alkali and MnO in slag fraction 5-10 mm

**Chemical composition of < 0.5 mm fines**

The fraction < 0.5 mm has high contents of C and Fe. The Fe content is especially high in samples taken close to the taphole in the upper cores. One sample of those taken beneath the raceway that contained considerable amounts of fines was analyzed using XRD. The XRD pattern is shown in Figure 18 and the result described in the text in connection to the figure.

Figure 15 Content of C and Fe in fines fraction < 0.5 mm

**Coke porosity**

The coke density and porosity were analyzed on coke from the 1st drilling campaign. The coke porosity and density, respectively, are of the same level for the major part of the samples analyzed but in samples from the lower part of hearth the porosity is lower and the density higher. Results from porosity measurements are shown in Figure 16. In the lower part of the hearth the chemical composition for coke is changed as well.

Figure 16. Porosity and mean pore diameter of coke samples taken during 1st drilling campaign

**Graphitization degree of 5-10 mm coke**

The calcined coke peak in diffractograms collected for each of the samples analyzed with XRD were used for estimation of the Lc value and corresponding graphitization degree. At slightly higher angles than the position of calcined coke peak, a peak corresponding to graphite and/or quartzite is often present. Diffractograms for coke samples from the EBF hearth have additional peaks not seen in laboratory treated samples. Figure 17 shows three diffractograms for samples taken beneath the raceway.
A preliminary identification of the peaks made based on calculations in the thermodynamic software Factsage and XRD evaluation program installed in the analyzes instrument has been made. A peak identified to correspond to both gehelenite and leucite, KAlSi$_2$O$_6$ is positioned at 2θ of ~ 31.22º and close to this peak at ~ 31.40º a peak probably corresponding to CaS is present. The formation of similar chemical compounds is found in the thermodynamic calculation result. Comparing with the chemical composition of coke and the position of peaks, leucite seems possible for one or two samples beneath the raceway but gehelenite and CaS seems to be present in more or less all coke samples. Solid compounds that might be present in specific temperature intervals according to the thermodynamic calculation are e.g. carbon, iron carbide, iron silicon, gehelenite (Ca$_2$Al$_2$SiO$_7$), akermanite (Ca$_2$MgSi$_2$O$_7$) and merwinite (Ca$_3$MgSi$_2$O$_8$), but most of the peaks for these compounds are outside the measured 2θ range.

The graphitization degree was estimated using XRD and the estimation method previously described and the results is shown in Figure 18. The graphitization degree of coke in the 5-10 mm fraction is in general quite high. Although the difference is not so significant samples collected beneath the raceway has a higher graphitization degree compared samples from centre or close to taphole. The with sample lowest graphitization degree is comparably high in content of alkalis in the ash.

For comparison a diffractogram for < 0.5 mm fines from the core beneath the raceway is shown with labels to the right in Figure 18. As there is a very strong peak at 2θ of approximately 26.6 other peaks are difficult to distinguish and therefore the scale for the y-axis was limited to a value much less than the counts collected for this peak. In similar way as for coke samples thermodynamic calculation was compared with the outcome from XRD. Several of the compounds predicted from calculation were similar as in case with coke but due to composition of the sample the amount calculated was different.
CONCLUDING DISCUSSION

Hearth Conditions
The wall temperatures, bottom temperatures and the temperatures estimated from the graphitization degree of coke indicate quite uniform temperature distribution in the EBF heart. The raceway in the EBF is quite long relative the hearth diameter. Therefore samples taken from the position of tuyere no. 3 and along the diameter to the taphole can be influenced by the combustion gas leaving the raceway. This can also be seen from the \( L_c \) values of coke samples at the uppermost position in the EBF heart. In this study only one diameter from tuyere no. 3 to the taphole is investigated. It could be expected that the temperatures in between the raceways could be lower. Further investigations are now carried out to describe the whole EBF hearth.

During dissection of the EBF heart after the campaign, char coal from the start up was found. This shows that the replacement time of coke in part of the furnace can be several weeks. The coke samples in the lowest part of hearth taken during the 1\(^{st}\) drilling campaign have high density and low porosity partly due to liquid penetration. Based on chemical analyses of coke similar results should be expected also for the 2\(^{nd}\) drilling campaign. The bulk density of the coke bed increases downwards in the hearth due to increased coke density, ratio of fines and ratio of metal. The bulk density estimated for deadman with and without the presence of hot metal and slag can be used for estimation of weather deadman is floating or not. However, in the EBF deadman is assumed to be sitting. The liquid filled up to quite a low level between the taps don’t have necessary buoyancy force for the burden column.

The bulk density estimated for the industrial furnace Kokura No. 2 was much higher compared to in this study\(^1\). The higher bulk density was caused by a pulverized coke and metal present in deadman and in the measured samples. Additionally, the density of coke should be increased more than in the EBF due to a higher liquid level between the taps. The coke in the EBF is also relatively fresh as the hearth is filled up with new coke at start up of the campaign.

Estimated bulk density, particle size distribution of magnetic material, slag and coke and the shape of metal and slag drops all indicate a smaller void fraction in the volume beneath the raceway. Some fines could be generated during drilling, especially when the bed is hard and fines can also move downwards during drilling but the shape of magnetic and slag should originate from the point of quenching. It is also known from practical work at industrial furnace that it can be very hard and dense material in the raceway bottom. If the reason is formation of a higher amount of fines in the turbulent raceway volume restricting the liquid flow or if the liquid flow is lower through the raceway due to the blast flow is not clear. Molten material can consume fines and keep the bed cleaner.

Flow of melt in EBF heart
The flow of melt can be estimated using process data and results in terms of bulk density, temperature distribution and particle size distribution of magnetic material, slag and coke. The hot metal flow is lower beneath the raceway compared to in the centre and close to the taphole. There are considerable amounts of magnetic material in the cores beneath the raceway but also a great part in the fraction between 1-5 mm. In the other part of the hearth the magnetic material is mostly > 5 mm. With a low void fraction small magnetic drops cannot flow and coalescence to greater drops. High momentum of gas in the raceway forces the flow of metal towards the centre of the blast furnace and at the same time fines generated in the raceway is transported downwards beneath the raceway.

A more direct way for the hot metal flow towards the taphole during the 1\(^{st}\) drilling campaign is indicated by thermocouple readings, hot metal quality and the “coke free space” close to taphole. The higher variation of one thermocouple close to the taphole could be caused by a higher flow of melt passing this point towards the taphole. Carburettor of hot metal occurs during interaction between hot metal and coke in the lower part of the blast furnace. If hot metal flows in the peripheral part a lower C content of hot metal relative the temperature could be expected as was the case when comparing 1\(^{st}\) and 2\(^{nd}\) core drilling campaign. Hot metal flowing through the coke bed can transfer heat to it at the same time as carburettor occurs and the temperature of hot metal becomes lower. The lower Si content in the centre and close to the taphole in the upper part of the hearth during 2\(^{nd}\) drilling campaign might be explained by a higher flow of melt (also slag) from the dripping zone through these parts of the diameter compared with through the raceway. Residual FeO in the slag can react with Si in hot metal.

Development of coke properties
On its way down to hearth coke properties has been influenced by the conditions in the shaft, at cohesive zone and at raceway level. The coke charged has low reactivity and high strength after reaction. Previous studies have shown that the influence of shaft conditions on coke gives only minor change\(^2\). The ash of the coke used in the EBF consists mainly of silicates that will sustain in the shaft and weakening of the coke occurs first at higher temperatures when the silicates are reduced to SiO(g) or transferred to silicon carbide.

During descending the graphitization degree of coke increases step by step when temperatures above \(~1050-1100~\)°C (the approximate coking temperature) are reached. Coke passes the raceway level down to the hearth and is affected by the high temperature corresponding to theoretical adiabatic flame temperature of \(~2050-2200~\)°C. The high flow of gas can transfer particles generated in the raceway to areas outside the raceway. Hot metal will also be able to heat the hearth coke up to tap temperatures of \(~1420-1480~\)°C. However, as the heat losses could be expected to be quite high in the fairly small furnace, higher in-furnace temperature of hot metal
could be possible. The temperatures that coke has been exposed to were estimated by graphitization degree estimations of coke samples from 1st and 2nd drilling campaign. Comparing data with results from other studies carried out, the graphitization degree corresponds to temperatures in the range of ~ 1700-1800 °C. The temperature at the location at which the coke sample was taken could have been lower than estimated with graphitization degree as coke can pass high temperature regions on its way down to hearth. The estimated temperature is highest in the hearth cores beneath the raceway and decrease in the centre and towards the taphole. A high graphitization degree of coke may lead to higher fines generation when it is exposed to some kind of wear.

Additional peaks on the diffractogram of coke samples and thermodynamic calculation results in Factsage® indicate that the alkali compound leucite (KAlSi$_2$O$_6$) and gehlenite (Ca$_2$Al$_2$SiO$_7$) may be present in the coke ash in a specific temperature range for each compound. As been the case in general for coke used in the EBF, XRD of coke that was used during the 2nd drilling campaign did not contain any peak at 31.2° prior charging. KAlSi$_2$O$_6$ is reported to be found also in the ashes from different combustion processes as e. g. in the combustion of biomass when compounds containing potassium, aluminium and silicon are present. Similar elements are present in the BF. Melting point of leucite is ~1530 °C and if it is present in coke samples of a high graphitization degree, two different temperatures can be indicated at the same time. In one sample beneath the raceway, not so far from hearth bottom leucite is indicated at the same time as graphitization degree is quite high. One explanation could be that coke pieces passing the raceway level are heated to high temperatures. Beneath the raceway the temperature decreases towards the bottom and if temperature less than 1530°C is reached compounds like leucite can persist if they are formed.

Increased ash content, increased density and decreased porosity of coke in the lowest part of hearth seem to be related to penetration of liquid into the pores of coke. The contents of ash, alkalis and other elements are high and at this level of hearth liquid are accumulated between the taps. The oxygen potential is low and CO dominates the gas atmosphere but the temperature may be slightly lower due to cooling through the furnace wall and bottom.

Suitability of used Methods

Measurements installed in the hearth shows the same levels of temperatures measured for the hearth wall and hearth bottom and that some variation could be connected to hot metal flow. This can be improved with a greater number of measurement points.

The method of taking core samples by drilling into the coke bed of hearth works well and the examination of cores reveals important information about hearth state. To state that the void fraction in general is low beneath the raceways and also examine the areas in-between the raceways it is necessary to drill a greater number of cores into the hearth. The sampling and analyzes have to be repeated to be able to distinguish between operational effects and normal variation.

For the estimation of graphitization degrees the 2θ range for measurements are quite narrow but accurate in the actual range. There are still some difficulties to make a good estimation due to disturbing peaks near the carbon 002 peak. For identification of other compounds a wider measured range should be needed. The evaluation of graphitization degree can be further improved and maybe strengthened by mineralogical analyses. Additionally, alternative sample preparation methods should be explored.

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