Effect of coal properties, injection rate and 
\( O_2 \) addition on BF conditions

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ABSTRACT

A test with different coal grades, injection rates and methods for oxygen addition has been performed in the LKAB experimental BF (EBF). The EBF test results are compared with results achieved at BF No. 3 at SSAB Tunnplåt in Luleå. The BF conditions have been studied by evaluation of process data, vertical temperature measurements and under-burden probe data in terms of temperature and gas composition. The generation of fines has been studied in samples taken out by solid sampling in the shaft and in samples of BF flue dust and sludge. The samples have been analysed by tumbler tests, chemical analyses, XRD and light microscopy. The type of PC used turned out to have a great effect on the consumption of reducing agents as well as on the dust generation. Effects seen on the BF gas composition and alkali behaviour that affected the raw material behaviour could be seen when the low volatile coal was changed into a high volatile coal. The vertical temperature profile was greatly influenced by the PCR, which also had an effect on the dust generation.

1 INTRODUCTION

The predominant way to produce hot metal is still the efficient BF process. To further improve the process from the environmental and economic point of view a continuous work to decrease the consumption of reducing agents is going on. The BF operation in Sweden is characterized by the use of 100% olivine pellets as iron burden material and high-quality coke resulting in a low slag volume and a low consumption of reducing agents. A cold-bonded briquette that is produced from in-plant fines is charged into the BF and PC is injected. In the effort to further decrease the total consumption of reducing agents and replace a larger ratio of the coke by PC a two-weeks trial in the LKAB EBF was carried out, as part of a large project, focusing on the effect of coal properties, injection rate and \( O_2 \) addition on the combustion of PC coal and the generation of fines and dust in the BF.

2 EXPERIMENT

2.1 EBF

The EBF has a working volume of 8.2 m³ and a hearth diameter of 1.2 m. There are three tuyeres arranged at intervals of 120° as shown in Fig. 1. The use of insulating refractories keeps the heat loss at a minimum. Only the bosh area and the tuyeres are water-cooled. The blast is normally preheated to 1200°C. The EBF is equipped with a bell-less top. Two mechanical stock rods monitor the burden descent and control the charging of the furnace. Pulverised coal (PC) is injected with an oxy-coal system and the coal lances are of swirl type. The furnace has one taphole, which is opened approximately once an hour with a drill and closed with a mud gun.

![Fig. 1. Position of tuyeres (T1-T3) and taphole at the EBF.](image)

Shaft probes for temperature measurement; gas analysis and solid sampling over the blast furnace diameter at two different levels in the BF shaft are used. Material samples are divided into sub-samples and the sample with the highest number origins from a location close to the BF wall. Vertical temperature measurements are made by having a thermocouple descend with the burden during manual registration of the temperatures. The exact route of the thermocouple cannot be controlled at vertical probing and the temperature between and above the tuyeres differs significantly. The positions of the upper and lower probes as well as the tuyere level are shown in Fig. 1. The horizontal probes are introduced between two tuyeres and end up above one tuyere at the opposite side of the furnace before the probing is finished.

2.2 Experimental conditions in the EBF

During the EBF test two coal grades, a high volatile (HV) one and a low volatile (LV) one, were tested. The pulverised coal injection rate (PCR) was varied and either \( O_2 \) or air added to the lance. The total \( O_2 \) enrichment was adjusted for the PCR. The test conditions and the measured PCR can be seen in Table 1 and the chemical composition of the raw materials used is stated in Table 2.

<table>
<thead>
<tr>
<th>PC type</th>
<th>PCR</th>
<th>Lance addition</th>
<th>Blast addition</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>A</td>
<td>152 ( O_2 )</td>
<td>( O_2 )</td>
</tr>
<tr>
<td>P2</td>
<td>A</td>
<td>146 Air</td>
<td>( O_2 )</td>
</tr>
<tr>
<td>P3</td>
<td>A</td>
<td>79 ( O_2 )</td>
<td>--</td>
</tr>
<tr>
<td>P4</td>
<td>B</td>
<td>94 ( O_2 )</td>
<td>--</td>
</tr>
<tr>
<td>P5</td>
<td>B</td>
<td>152 ( O_2 )</td>
<td>( O_2 )</td>
</tr>
<tr>
<td>P6</td>
<td>B</td>
<td>143 Air</td>
<td>( O_2 )</td>
</tr>
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</table>
Table 2 Chemical composition of raw materials used in the EBF test. (VM=volatiles, H₂O=moisture)

<table>
<thead>
<tr>
<th></th>
<th>Pellet</th>
<th>Quartz-</th>
<th>BOF slag</th>
<th>Lime-</th>
<th>Coke</th>
<th>PC A</th>
<th>PC B</th>
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</thead>
<tbody>
<tr>
<td>Fe</td>
<td>66.77</td>
<td>0.65</td>
<td>19.5</td>
<td>0.17</td>
<td>0.39</td>
<td>0.44</td>
<td>0.32</td>
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<tr>
<td>CaO</td>
<td>0.38</td>
<td>0.46</td>
<td>42.6</td>
<td>54.8</td>
<td>0.058</td>
<td>0.32</td>
<td>0.18</td>
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<td>MgO</td>
<td>1.50</td>
<td>0.80</td>
<td>9.03</td>
<td>0.74</td>
<td>0.055</td>
<td>0.099</td>
<td>0.13</td>
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<tr>
<td>SiO₂</td>
<td>1.75</td>
<td>90.5</td>
<td>8.30</td>
<td>1.05</td>
<td>5.96</td>
<td>2.79</td>
<td>3.87</td>
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<tr>
<td>Al₂O₃</td>
<td>0.33</td>
<td>5.67</td>
<td>1.47</td>
<td>0.50</td>
<td>2.71</td>
<td>1.80</td>
<td>1.26</td>
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<tr>
<td>TiO₂</td>
<td>0.31</td>
<td>0.10</td>
<td>1.83</td>
<td>0.020</td>
<td>0.18</td>
<td>0.058</td>
<td>0.058</td>
</tr>
<tr>
<td>V₂O₅</td>
<td>0.22</td>
<td>0.060</td>
<td>5.12</td>
<td>0.040</td>
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<tr>
<td>Na₂O</td>
<td>0.051</td>
<td>0.020</td>
<td>3.86</td>
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<tr>
<td>K₂O</td>
<td>0.020</td>
<td>0.010</td>
<td>0.050</td>
<td>0.20</td>
<td>0.58</td>
<td>0.40</td>
<td>0.67</td>
</tr>
<tr>
<td>S</td>
<td>0.001</td>
<td>0.010</td>
<td>0.050</td>
<td>0.20</td>
<td>0.58</td>
<td>0.40</td>
<td>0.67</td>
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<tr>
<td>MnO</td>
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<td>0.020</td>
<td>3.86</td>
<td></td>
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<td></td>
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<tr>
<td>CO₂</td>
<td>0.60</td>
<td>0.10</td>
<td>0.10</td>
<td>1.0</td>
<td>5.2</td>
<td>1.0</td>
<td>0.90</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.60</td>
<td>0.10</td>
<td>0.10</td>
<td>1.0</td>
<td>5.2</td>
<td>1.0</td>
<td>0.90</td>
</tr>
</tbody>
</table>

2.3 Experimental results in the EBF

Process – The test was characterized by stable operation conditions except for a cold thermal state of the EBF that occurred after the change-over from PC A to PC B. The consumption of reducing agents increased when the LV PC A was exchanged by HV PC B as can be seen in Fig. 2.

Gas and temperature profiles – The vertical temperature profile was measured for each operational parameter setting and the horizontal temperature and gas profiles were measured with the probes at the upper and lower positions. The results obtained from the vertical probing indicate that the temperature of the thermal reserve zone is independent of the PCR but that the temperature rise occurs earlier when the PCR is increased. The type of coal injected has no significant effect. Fig. 5 shows the effect of PCR on the position of the thermal reserve zone and its temperature.

Fines – Fines generated in the EBF are studied in the probe samples (-0.5 mm and 0.5-3 mm fractions), in the BF flue dust and in the BF sludge. The basicity of BF flue dust increases when the basicity of the slag is increased. As can be seen in Fig. 6 the amount of BF flue dust and sludge is higher during P4-P6 when the HV PC B is injected compared to during P1-P3 when the LV PC A is injected.
The changes in the chemical composition of the sludge and the changed amount greatly affect the losses of different compounds through the BF top. As can be seen in Fig. 7 the losses of Fe and C are greater when the HV PC B is injected during P4-P6. The amount of SiO₂ and alkalis per tHM is also larger and the contents of alkalis and SiO₂ in the sludge are correlated as can be seen from Fig. 8.

**Fig. 7** Losses of compounds with the BF sludge.

![Graph showing losses of compounds with the BF sludge.](image)

**Fig. 8** Contents of alkalis and SiO₂ in the sludge

The changed behaviour of alkalis is also indicated by analyses of the probe samples. As can be seen from Fig. 9, the alkali content of –0.5 mm fines increases downwards in the BF shaft and the highest values are reached during injection of HV PC B. Analyses of the fraction 0.5-3 mm from samples taken with the lower shaft probe show a difference in alkali content over the BF diameter. The amount of alkalis analyzed in the sub-samples taken with the lower probe correlates best with the content of Al₂O₃.

**Fig. 9** Content of Na₂O and K₂O in –0.5 mm fines in samples taken with the upper and lower shaft probes.

XRD analyses of BF sludge shown in Fig. 10 are disturbed by the presence of amorphous phases, but they still indicate differences in the phases present at different operational conditions. The intensity of the peaks corresponding to calcite and magnetite is higher when PC B is injected at a high rate and especially if air is added to the lance instead of oxygen. The high SiO₂ content in the sludge is not correlated to any phase by the XRD analyses. However, when injecting the LV PC A with a ratio of SiO₂/Al₂O₃ of 1.5 the same ratio is 1.3-1.5 in the sludge and when injecting the HV PC B with a ratio of 3 the value of the sludge is 1.8-2.1. The SiO₂/Al₂O₃ ratio is approximately 2 for coke.

**Fig. 10** Phases present in BF sludge (asterisk: hematite, ▼: calcite, ▽: magnetite).

### 2.4 Operational results at BF No. 3, Luleå

BF No. 3 was rebuilt in the summer of 2000. It has a working volume of 2,540 m³ (a total volume of 3,224 m³) and the hearth diameter is 11.4 m. In 2005, 2,300 ktonnes of hot metal was produced with a slag ratio of 165 kg/tHM. The burden is 100% olivine pellets, together with limestone, BOF slag, briquettes and Mn slag as additives. The coke used is mainly produced at SSAB except for about 10% that has to be purchased. In 2005, the coke rate was 322 kg/tHM and the PCI rate 142 kg/tHM, which gives a total reductant rate of 464 kg/tHM.

During the 90’s the HV coal was the coal most frequently used and preferred. Trials with LV coal showed quick positive effects on the reductant rate, the decrease was in the order of 10 kg/tHM. The furnace behaviour was trouble-free and the hot metal quality well within normal variations. Gradually LV coal came to substitute HV coal and today almost 100% of the coal used for PCI at the SSAB works in Luleå is LV coal.

Another observation made when introducing LV-coal had to do with the properties of the BF sludge. At BF No. 3 flue dust is separated in two steps, first dry separation in a dust cyclone and then wet separation in a scrubber. The dust from the wet scrubber is pumped as a sludge to a deposit situated 2 km from the blast furnace. The scaling in the pumps and pipes that transport the sludge to the deposit has been a problem. It could be noticed that when LV coal was introduced the speed of the scale formation was reduced. As a result, the interval between high-pressure cleaning of the pipes could be increased.

### 3 Discussion

The injection rate of PC has shown to have a great effect on the vertical temperature profile of the BF and in
addition the temperature increases faster in the shaft when the PC rate is increased. A higher gas volume increasing the thermal capacity of the ascending gas might be the main explanation of this, an increased reduction potential of the gas may give a minor effect. The considerably high temperature (1050°C) measured in the thermal reserve zone during vertical probing is mainly caused by the low reactivity (CRI – 20%) of the coke produced at SSAB. Coke samples taken with the burden probes during operation were hardly affected at all by the BF atmosphere indicating that the solution loss reaction is not taking place to a great extent. The measured temperature correlates with a high CO and a low CO₂ of the gas.

The generation of fine dust collected as sludge is higher when injecting PC B compared to when using PC A, especially at a high injection rate. The composition and amount of sludge seem to be correlated mainly to the conditions at the lower part of the BF. The use of PC B leads to increased losses of especially C, but also of Fe. Higher losses of C may be caused by a lower efficiency in the use of the injected PC. A higher amount of SiO₂ is leaving the BF when PC B is injected and the SiO₂/Al₂O₃ ratio of the sludge is also higher in spite of a decreased charging of quartzite and a higher basicity of the final slag. This can be explained by the ash composition e.g. SiO₂/Al₂O₃ ratio that is much higher for the PC B as previously mentioned. The activity of SiO₂ is higher in the ash of PC B and therefore the generation of SiO(g) will also be higher. The evaluation of XRD analyses does not show the presence of any phase containing Si, which indicates that such a phase is amorphous. If SiO(g) generated in the raceway is oxidized and rapidly condensed further up in the shaft it will probably form an amorphous phase. Alkalis can as well be condensed on these particles and the content of alkalis in the sludge correlates with the content of SiO₂. It seems reasonable that an increased SiO(g) generation shall result in an increased reduction and vaporization of especially K, but also Na that to a great extent are contained in silicates. The increased slag basicity when injecting PC B leads to a decreased absorption of alkalis in the slag.

There are several reasons for the significantly lower consumption of reducing agents when using PC A. The decrease is greater than can be explained by the higher heat value and C content of PC A. Additional reasons are the greater losses of C with the dust as described above. The differences in the SiO(g) generation and alkali recirculation are probably more pronounced in the EBF because of the high ratio of raceway area to total cross sectional area. In an industrial BF the raceway length is much shorter than the BF radius and the “dead man” fills up the centre region. This may also be the main explanation of the larger difference in the consumption of reducing agents in the EBF compared to that in BF No. 3 at SSAB.

The experience both at the EBF and at BF No. 3 shows that the amount and nature of the sludge changes with the coal type. The higher content of Fe, when injecting the PC B, increases the density of the sludge and makes it more difficult to transport. Peaks with higher intensity of magnetite are found in the XRD analyses at a high injection level of PC B, which implies that Fe³⁺ is present. Factors that can contribute to this are first the higher content of volatiles that generates H₂ and that affects the reduction potential of the gas and secondly the greater amount of alkalis detected in the solid samples from the EBF. Alkalis catalyse the reduction reaction and can increase the swelling of iron burden. Fe²⁺ can be oxidized to Fe³⁺ in the pumps and pipes and when the dissolution constant is exceeded a solid phase that builds up scales in the pipes can be formed. CaCO₃ indicated by the XRD analyses may as well be formed after the addition of water and in that case it will be active in scale formation.

4 Conclusions

A test with different coal grades, injection rates and methods for oxygen addition has been performed in the LKAB experimental BF (EBF). The same types of PC have been tested in BF No. 3 at SSAB with similar results. The test results show a significantly lower consumption of reducing agents with LV PC A compared with HV PC B due to:

- a higher heat value and C content
- a lower dust generation resulting in lower losses

A lower generation of dust with LV PC B is due to:

- a higher total use of injected PC resulting in lower "soot/char"
- a lower SiO₂/Al₂O₃ ratio resulting in less SiO(g) generation
- a lower recycling of alkalis

A changed amount of sludge and a change of its properties will result in less scale formation during sludge transportation with LV PC A due to the fact that:

- Fe is present mainly as Fe³⁺
- a lower content of ions that form CaCO₃

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