INJECTION OF PULVERIZED MATERIALS INTO THE BLAST FURNACE RACEWAY

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Abstract
A number of injection trials carried out over the years at the LKAB experimental blast furnace (LKAB EBF®) and in industrial BFs shows that tuyere injection is a feasible method for supply of various types of pulverized materials as different types of PC, BOF slag and BF dust to the BF. In this study, the effect on process, raceway conditions, hot metal quality, reductant agent consumption and slag formation due to the selection of injection materials are discussed based on trial data. A special attention is paid on the injection of alternative carbon containing residual material. Based on recent trials the efficiency in use of carbon in injected residual materials are discussed and pilot scale results compared with industrial trial results.

Key words: Injection; Combustion; Tuyere slag; Reducing agents.

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Complementary injection of reducing agents as oil, gas, and pulverized coal (PC) is feasible aiming to reduce the coke consumption and costs for hot metal (HM) production. Other materials used on industrial scale with good results are e.g. plastics, grease and tar. In Europe the use of PC is dominating and efforts for increased injection rates have been made. One important factor for reaching high injection and replacement ratio for coke is the selected PC type for injection. The volatile matter (VM) content as well as ash composition and amount is important factors. From economical point of view flexibility in the use of different types of PC is important and alternative coals have to be considered constantly.

In early nineties injection trials with basic fluxes, sinter fines and iron ore fines were carried out in Japan aiming to control the HM quality \cite{1,2}. Lime and dolomite was shown to reduce and stabilize the Si and S contents while the main effect from injection of iron oxide was reduced Si content. Using sinter fines with both iron oxide and relatively high basicity had effects on both.

In Nordic BFs operate with low slag volume, on almost 100% pellets with basic fluxes (limestone, BOF slag) added from the top to adjust the slag composition. In the cohesive zone the fluxes are combined with gangue from the ferrous material but, as most of the ash is released in the raceway, the formed bosh slag will have excessive basicity. The excess in basicity is moderate with olivine pellets but with a fluxed pellets with primary basicity of B2=1 and low slag volume the excessive basicity of bosh slag becomes critical. Slag formation problems were experienced during operational trials with fluxed pellets due to the formation of a calcium silicate slag with low melting point as long as FeO is present. The melting point of this slag increases sharply when iron oxides are reduced into Fe_{\text{met}}. If the increase in melting point exceeds the increase in temperature moving downwards in the BF, the liquid slag may solidify. By tuyere injection \cite{3} the excessive bosh slag basicity can be avoided at the same time as basicity of tuyere slag \cite{4} increases and the slag properties becomes more uniform along the BF height.

The injection of PC as well as of basic fluxes and ferrous fines shows that injection into the BF is feasible for a wide range of pulverized materials. Legalizations and limited landfill areas demands return of in-plant fines to the process and without sinter plants recycling options for fine particulate residues may be either cold-bonded agglomerates or tuyere injection. In case of capacity restriction in briquette production or negative influence from a material on the quality of agglomerates recycling via injection could be an option. Returning BF flue dust \cite{5} (BFD) directly from the dust catcher or cyclone back to the BF increases the efficiency in originally charged materials by returning contained coke fines and fines from ferrous materials and fluxes. \cite{6,7}

The injection materials influences the raceway conditions and thereby the HM compositions. It has e.g. been stated that the Si transfer from injected PC is faster than from coke combusted in the same region \cite{8} and that increased ratio of SiO2/Al2O3 also increases the transfer, probably due to increased activity of SiO2 in the ash. Increased basicity of the tuyere slag results in decreased activity of SiO2 in the tuyere slag and following less reduction and SiO(g) formation and dissolution of Si into the HM. The basic oxides also binds S. Increased FeO content and correspondingly higher oxygen potential will decrease the reduction to SiO(g) and Si dissolved in the HM will react with FeO and become oxidised. The tuyere slag
viscosity becomes lower and the permeability at the tuyere level is improved which results in better S refining.

The LKAB Experimental BF (LKABs EBF®) offers a unique possibility to study the effects from injection of various types of materials before conducting trials on industrial scale. The limited amount of materials necessary for a pilot-scale trial is a great advantage. In different injection experiments the EBF was used in investigations for later possible implementation on industrial scale. HV and LV PC injection\(^{(9)}\) were carried out, BOF slag\(^{(3)}\) has been injected for investigation of the slag formation and the energy efficiency in the recycling of BF sludge (BFS) and BFD via injection studied.\(^{(10,11)}\) The investigations include indirect or direct studies on the effect of injection of the raceway conditions as well as the overall operational results and feasibility for industrial implementation is discussed. A special focus is made on recent trials with injection of alternative carbon materials (ACM) in terms of BFD injection in pilot and industrial scale BF.

2 MATERIALS AND METHODS

2.1 The LKAB EBF®

A schematic layout of the LKAB EBF plant erected in 1997 is shown in Figure 1. Up to the present totally 28 campaigns with many types of trials have been conducted. Operational behaviour and process results have been analysed for various types of pellet burden separately or mixed with sinter, lump ore, and cold bonded pellet made from in-plant fines. The effects of injection of different types of PC, oil, gas, additives and titanium bearing materials have been studied and the blast conditions varied. In the ULCOS project reduction of CO\(_2\) emission has been investigated in trials with charging of pre-reduced burden and by recycling of top gas after CO\(_2\) removal. The EBF can be modified and adapted to desired operational conditions and new process concepts to be tested. After most campaigns the EBF is quenched with N\(_2\) from the top and after a couple of weeks of cooling the excavation can start.

Operation of the EBF is quite similar to an industrial BF in terms of the process control system and automation, but the response time after a change is shorter. The EBF has one taphole, which is opened with a drill and closed with a mud gun. The HM and slag is tapped together into a sand-filled box. The raw material handling system consists of four pellets bins, one coke bin and four hoppers for additives. Weighed material is transported to the bell-less top and distributed as desired when indicated by the mechanical stock rod that monitors the stockline level. The EBF has a working volume of 8.2 m\(^3\) 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 and heat losses minimised by use of insulating refractories. Only the bosh area and the tuyeres are water-cooled. The EBF is operated with an excess top pressure up to 1.5 barg and the blast, with O\(_2\) addition if desired, can be preheated to 1200°C in pebble bed heaters.
O₂ addition to the lance in combination with a swirl-type tip results in high combustion efficiency of PC. Injection trials with addition of a second pulverized material was in earlier trials with BOFS carried out by using a separate vessel and a screw-feeder supplying the fines of additives in to the fluidisation chamber of PC. In recent trials PC and Tornado treated BFS/dry BFD was mixed during filling the PC system.

2.2 BF No. 4 at SSAB in Oxelösund

The BFD injection plant installed at BF No. 4 at SSAB Oxelösund is shown in Figure 2. The BFD is injected in separate lances of straight pipe type installed in every second tuyere out of totally 20 which are equipped with swirl-tipped oxy-coal lances for PC. As can be seen the BFD is transported directly from the dust catcher to the injection plant and so far the BFD from BF No. 4 is recycled back.

When the BFD is not injected it is allowed to accumulate in a feed hopper above the dust pump as the dust discharges due to gravity. The BFD is pneumatically conveyed
with air through a steel pipework to the injection house that includes a silo, a lock vessel, a dispense vessel and a rotoscrew feeder. The rotoscrew feeder transports BFD to the splitter, from which it is injected into the BF. For uniform distribution the injection system is designed for similar pressure drop in all injection lines.

2.3 Materials

Table 1. Data for the operational trials in the EBF. BFS=BF sludge, BFD= BF flue dust, BOFS=BOF slag, limestone=LS, Quartzite=Q, olivine pellets=PO, Fluxed pellet=PB

<table>
<thead>
<tr>
<th>PC types</th>
<th>Injection of BOFS</th>
<th>Inj. of BFS/dust</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ref.</td>
<td>BOFS1</td>
</tr>
<tr>
<td>Ferrous mtrl</td>
<td>100% PO</td>
<td>30% PO</td>
</tr>
<tr>
<td>Additives</td>
<td>Q, LS, BOFS</td>
<td>Q, LS, BOFS</td>
</tr>
<tr>
<td>Slag rate</td>
<td>154-171</td>
<td>149-159</td>
</tr>
<tr>
<td>B2</td>
<td>0.8-1.0</td>
<td>0.83</td>
</tr>
<tr>
<td>Coke rate</td>
<td>414-480</td>
<td>400-452</td>
</tr>
<tr>
<td>PC type</td>
<td>HV</td>
<td>LV</td>
</tr>
<tr>
<td>PCR</td>
<td>79-152</td>
<td>98</td>
</tr>
<tr>
<td>Inj. additive</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Add. rate</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Blast vol.</td>
<td>1730</td>
<td>1730-1745</td>
</tr>
<tr>
<td>Blast T</td>
<td>1130</td>
<td>1130 °C</td>
</tr>
<tr>
<td>Lance O2</td>
<td>0-40</td>
<td>------</td>
</tr>
<tr>
<td>Blast O2</td>
<td>40-80</td>
<td>16.1</td>
</tr>
<tr>
<td>Blast H2O</td>
<td>11.5</td>
<td>15</td>
</tr>
<tr>
<td>C</td>
<td>3.6-4.4</td>
<td>4.0-4.2</td>
</tr>
<tr>
<td>Si</td>
<td>1.1-1.5</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>HM Temp</td>
<td>1423-1461</td>
<td>1393-1446</td>
</tr>
</tbody>
</table>

The raw materials used for different types of injection trials in the EBF are stated in Table 1. The injection trials with HV and LV PC as well as the ones with injection of BFD were also carried on industrial scale with corresponding effects. As can be seen the use of coke and PC as well as the resulting HM properties varies significantly also within the same trial.

Table 2. Raw materials and blast parameter settings at SSAB BF No.4

| Ferrous material | Ref | Test | Blast vol. | 1038 | 1004 Nm³/tHM |
| Additives | LS, BOFS | Blast T | 990 | 977 °C |
| Slag rate | 143 | 143 | kg/tHM | Lance O2 | 15 | 14 Nm³/tHM |
| Bas B2 | 0.91 | 0.94 | Blast O2 | 9 | 18 Nm³/tHM |
| Coke rate | 400.2 | 390.2 | kg/tHM | Blast H2O | 6.4 | 20 g/Nm³ |
| PC type | LV | C | 4.38 | 4.38 wt.% |
| PCR | 80 | 75.6 | kg/tHM | Si | 0.68 | 0.71 wt.% |
| BFD Inj. rate | 14.8 | kg/tHM | Temp | 1474 | 1485 °C |

The materials and blast parameters for the industrial trials at SSAB the burden with, additives and PC type were used as stated in Table 2. Oxygen and moisture addition is higher during the BFD injection period compared to during reference period. As explained previously BFD and PC are injected through separate lances and O₂ is supplied to the PC lance.
3 RESULTS AND DISCUSSION

3.1 Feasibility of Injection of Pulverized Material into the BF

The tests with injection of pulverized materials into the EBF and on industrial scale shows that it is a feasible method for various types of materials and that quite high amount of additional material can be mixed with PC. For the BFD it has been proven that injection of BFD and PC through separate lances is feasible as well. However, independent on injection method used the raw material handling and injection system demands some special thoughts and it has to be adapted to the abrasiveness of the actual material to be injected. The BOFS is due to contained Fe met quite difficult to grind and causes wear during milling, ~7 times higher than for a hard coal. From earlier trials\(^\text{(13)}\) it is known that the coke breeze in BFD may cause abrasion. For the recent test with injection of BFD the PCI system at the EBF was modified to minimize turbulence e.g. by making bends smooth and eliminate dimension changes at connections. Measurements of pipe thickness during the test did not indicate any problems but for long-term injection, bends with protective lining is recommended. For the industrial installation alumina lining was used at positions subject to specific wear.

![Figure 3. BRI and %Si in HM as heat level indicator with increased injection rates of ACM.](image)

![Figure 4. BRI and %Si in HM as heat level indicator with increased injection rates of BOFS.](image)

When injecting BFS, BFD and BOFS increased burden resistance index (BRI) or increased pressure drop over the burden column as shown in Figure 3 and 4 can be seen in the EBF. However, operation with injection rates of BFD up to 40 kg/tHM was characterised by stable process conditions. At higher injection rates channelling was experienced from time to time. With BOFS injection the resistance increase is most significant at each step of raised injection rate and the effect is reduced after stabilization of the operation conditions. During the tests with BOFS the burden is also changed for each trial step and e.g. at the last increase of BOFS injection rate the ferrous burden was shifted to 100% of PB and addition of additives reduced as shown in Figure 5. The highest injection rates used during EBF trials were ~37 kg/tHM for BOFS and ~60 kg/tHM for BFD. In the industrial trial with injection rates of ~20 kg/tHM in average (corresponds to 40 kg/tHM on each tuyere), significant effects on pressure drop or raceway depth was not seen (Figure 6).
Stable operation demands known replacement ratio of coke with injected reducing agents. The chemical composition of injected material has to be well-defined to avoid process disturbances. BFD and PC could be uniformly mixed and transported without segregation but not the mix of BFS and PC. A proportionally higher ratio of BFS than expected caused C input deficiency, depletion of coke reserve and low thermal level.\(^{(10)}\)

### 3.2 Effects on Raceway Conditions

The raceway conditions have in connection to different trials been investigated during excavation for all coke operation, injection of HV PC, with or without BOFS\(^{(3)}\) addition and by evaluation of drilled cores for all coke and injection of LV PC with or without BFD injection.\(^{(10,11)}\) In general, an impact from iron oxide and basic oxides on the raceway conditions could be stated by solid sample evaluation. Comparing tuyere samples\(^{(3)}\) from all coke operation with injection of PC or a mix of PC and BOFS by chemical analyses, XRD and SEM, it can be seen that the FeO and MnO content is quite high during all coke operation, much lower with PCI and intermediate with BOFS addition to PC. The measurements as well indicate that the slag formed during co-injection of PC and BOFS often contains magnesia as one part of the phase.

60-70 cm long raceway core samples were collected during short BF stoppages after operation with LV PC injection (146 kg/tHM) and injection of a mix corresponding to 27% BFD mixed with 73% LV PC (total injection rate ~155 kg/tHM). Part of the examination results are illustrated by Figures 7 to 10. The results for the PC/BFD conditions include less disintegration of coke but higher contents of tramp elements and iron oxide in the first part of core (close to the tuyere nose). The oxidation degree...
of iron is stated by chemical analyses and XRD evaluation as shown in Figure 9. In the core corresponding to PC only Fe is well reduced. Moreover, the lowest SiO$_2$/Al$_2$O$_3$ ratio in coke correlates with highest graphitisation degree\(^{(11)}\) which correspond to the higher temperature. The graphitisation degree of coke is lower with compared to without BFD addition to the PC.

Figure 9. Fe compounds in < 0.5 mm fines in raceway core sub-samples inj. BFD&PC.

Coke and PC fines can be consumed in direct reduction of e.g. FeO. The residual FeO and basic fluxes will improve the melting behaviour of tuyere slag. An as can be seen from Figure 10 the ratio of melted slag, estimated by thermodynamic simulations in FactSage\textsuperscript{®}, is higher with injection of BOFS and BFD compared to with injection of PC only. The melting properties are better in case of injecting 24 kg BOF slag/tHM compared to when using 37 kg/tHM due to reaching slightly too high basicity for the tuyere slag. Higher PC rates especially with the LV PC is favourable for melting behaviour of tuyere slag in comparison with higher coke consumption at raceway level. This is due to the ash compositions and lower melting point of PC ash in comparison with coke ash.

The permeability in the raceway region is improved by the consumption of coke and PC fines and improved melting properties of tuyere slag when BOFS or BFD are injected. This is favourable for S refining, which was indicated both in previous industrial trials\(^{(12)}\) and the present one as shown in Table 3. In previous EBF trials with moderate injection rate of BFD and the BOFS injection trials changed raceway conditions with additive injection had a quite strong impact on the HM quality. This cannot be seen in the trials with HV and LV PC or the high injection rate trials with BFD. A possible explanation is the use of oxy-coal system for the latter. The significant reduction in HM Si content and slag rate resulted in lowered RR in terms of 11 kg coke/tHM comparing the reference period with the period injecting 37 kg BOFS/tHM (Table 1).

There is a correlation between raceway conditions to sludge composition. In the tests with HV and LV PC a higher ratio of SiO$_2$/Al$_2$O$_3$ can be seen in the sludge when the HV PC with higher SiO$_2$/Al$_2$O$_3$ ratio in ash is injected. SiO$_2$ content in the sludge is correlated to its alkali content, indicating that SiO$_2$ and alkalis are reduced and gasified simultaneously in the raceway. Similar relationship has been seen for different trials including the ones with high injection rates of BFD. The alkali and SiO$_2$ correlation in the sludge is shown in Figure 11. Although that the bosh slag basicity is lower during BOFS injection (BOFS, B$_2$–4) the content of alkali oxides is higher at a specific concentration of SiO$_2$ in the sludge. However, for this trial the tuyere slag basicity is higher and the activity of SiO$_2$ lowered at the same time as the activity of
alkali oxides are higher. For BFS/BFD injection the case is opposite compared to injecting HV and LV PC. The addition of BFD according to Figure 10 results in higher SiO₂ content and ratio of SiO₂/Al₂O₃ at the same time as the basicity is lowered.

Figure 10. Estimated % slag melted for injection for BOFS & BFD trials in Table 1.

Figure 11. Alkali content as function of SiO₂ in sludge for injection trials in Table 1.

3.3 Accumulation of Tramp Elements

Due to the Zn and alkalis contained in BFD and BFS, injection will influence the load of the elements on the BF. The contents of Zn and alkalis in the raceway region increase as shown in Figure 12. Based on long term experience, reported by SSAB EMEA in Luleå, from recycling the generated BFD back into the BF it seems clear that this is possible in combination with the base of high quality raw materials with low contents of the compounds. Considering the recycling of BFD from two or more BFS back to one, or recycle both BFD and BFS back, the loads will increase further and the bleed out of Zn and alkalis through the BFS will not be enough. Although that the EBF trials of ACM was short, an increased and varied percentage output of Zn in the dust and sludge could be seen and were related to the top temperature as shown in Figure 13. The increase of tramp elements could also be seen in the sludge and dust generated during the test.

3.4 Energy and Material Efficiency of Injected BFD and BFS

During the EBF trials the HM heat level varied between the trial periods and as this has impact on the reductant rate (RR). In the left diagram of Figure 14 the variation in HM Si and temperature content is shown trial steps. During the BFD and BFS
injection trials the efficiency of injected C was explored using heat and mass balance calculations after normalising the HM chemical and thermal state. The trials in the EBF showed that C in BFD replaces C in injected PC and top charged coke on 1:1 basis as can be seen from the right part of Figure 14. The C in BFS replaced more or less no C in coke or PC, probably due to the process disturbance caused by C deficiency as a result from segregation of BFS/PC mix during transportation. It is believed that the C efficiency could be higher but further investigations are needed. One possibility should be using a separate injection system for BFS.

Figure 14. Variation in thermal level during trial exemplified by wt% Si and HM temperature(left) and C rate for normalised EBF heat level conditions (right).

Table 3. Trial periods in BF no 4 at SSAB EMEA in Oxelösund

<table>
<thead>
<tr>
<th>Ref, 10&quot;-20&quot; Feb. (264 h)</th>
<th>Test, 15&quot;-19&quot; Jun. (85 h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production rate</td>
<td>105.5</td>
</tr>
<tr>
<td>Reductant rate</td>
<td>480.2</td>
</tr>
<tr>
<td>BFD injection</td>
<td>0</td>
</tr>
<tr>
<td>Net C input</td>
<td>405.7</td>
</tr>
<tr>
<td>HM S</td>
<td>0.065</td>
</tr>
</tbody>
</table>

During full scale trials at SSAB in Oxelösund the calculated energy efficiency of injected BFD was even higher than for the EBF trials. Injection periods with BFD were most frequent during the spring 2011. From beginning of March until June BFD was injected the major part of the BF operation time. For comparison of C input the longest period with injection of BFD is compared with a stable period and lowest C rate without injection. Both periods are of the same heat level with a better S refining during the test period as can be seen in Table 3. However, as the slag basicity is also slightly higher during the test period this will also contribute to better S refining.

4 CONCLUSIONS

Tuyere injection is a feasible method for addition of different types of fine particulate raw materials to the BF separately or in a mix with PC. However, the raw material preparation and handling are sometimes difficult and has to be carefully analysed and adapted to each type of material (metallic inclusions in BOFS, abrasive coke fines in BFD and extremely fine particles in BFS)

Energy efficiency for C in injected BF dust is of the same level as for injected PC. Due to segregation problems the C efficiency of BFS could not be determined. There is an upper limit above which fines of injected material are not consumed with the same rate as it is injected with. This may cause accumulation of fines, decreased permeability at tuyere level and also increased direct reduction if iron oxide that has not been properly reduced.
At a proper injection level the raceway conditions are improved by improved melting properties of the tuyere slag, consumption of coke fines in direct reduction with FeO. As a result the S refining can be improved and slag formation over the radius becomes homogenous.

The BF load of specific tramp elements as Zn and alkalis contained in the BFD will be increased and the output relative input has to be monitored on regular basis to avoid accumulation. This will be especially important if both BFD and BFS is considered for recycling or BFD from two or more BFs are recycled back to one BF. Injected PC decreases the melting point of tuyere slag as the coke ash has a relatively lower melting point compared with coke ash.

Acknowledgements

The research work presented in this paper was carried out within Swedish national projects carried out within the organization of Swedish Steel producers and financed by Swedish Energy Agency as well as Flexinject RFSD-CT-2008-000001 funded by the Research Fund for Coal and Steel (RFCS) with additional financial contribution from Swedish Energy Agency. Part of the work has been carried out within CAMM, Centre of Advanced Mining and Metallurgy, at Luleå University of Technology.

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