The Effect of BOF Slag and BF Flue Dust on Coal Combustion Efficiency

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Injection into a BF of BOF slag to improve the slag formation and of BF flue dust to improve the recycling of in-plant fines has previously been tested. The effects on the PC combustion efficiency at different conditions, when these materials are co-injected with coal, have so far not been tested. Combustion efficiencies at varied temperature, O2 enrichment, amount of PC, amount of added BOF slag or BF flue dust and particle size of the added material are measured in a fixed bed and a blowpipe model. The established facts that an increased temperature and O2 enrichment or a decreased amount of coal increase the combustion efficiency are valid also when BOF slag or BF flue dust are added to the coal. By adjusting the combustion conditions, a decreased combustion efficiency can be counteracted, when a second material is co-injected with coal. The effect of BOF slag addition on coal combustion efficiency measured in the blowpipe model is insignificant, if a fine fraction is used. The combustion efficiency is higher in the fixed bed compared with that in the blowpipe model. The addition of BF flue dust increases the combustion efficiency in the fixed bed.

KEY WORDS: BOF slag; BF flue dust; combustion efficiency; raceway; injection.

1. Introduction

In the blast furnace, combustion and raceway conditions are controlled by adjustment of the tuyere parameters. The control parameters are blast temperature, oxygen enrichment, moisture content and injection rate. The coal injection rate has been gradually increased, the O2 enrichment has increased and at the same time the coke rate has decreased. This has changed the raceway conditions significantly. Multi-injection has also been considered for different reasons. The injection of basic fluxes or iron oxide has been tested to decrease the silicon content of hot metal1–7) and to improve slag formation.8,9) Additionally, the injection of different by-products has been evaluated for re-use of valuable components as well as to decrease the landfill.10–13)

The blast furnace at SSAB Luleå Works operates with 100% olivine pellets with an iron content of approximately 67%. Basic fluxes are charged together with the pellets from the top and the slag volume is 160–170 kg/HM. To further improve the BF process, a fluxed pellet with a basicity of CaO/SiO2=11, a low gangue content, good reducibility and suitable softening and melting properties, was produced and tested. However, in further studies, slag formation problems were revealed in full-scale tests, evaluated in a theoretical estimation14) and later verified in the laboratory.15,16) A slag of an excessive basicity and with a high melting point that increased during further reduction was formed in the bosh as a result of an interaction with basic fluxes in the burden. The high basicity slag was combined with an acid tuyere slag to form the final slag of a desired basicity. The studies indicate that by injecting the basic fluxes the formation of a slag of an excessive basicity can be avoided. A laboratory study on the effect of different basic fluxes—BOF slag, burnt lime and burnt dolomite—on the melting properties of tuyere slag shows that the addition of basic fluxes in general, and BOF slag particularly, improves the melting properties of coal and coke ash in terms of a decreased melting point and a decreased softening and melting temperature interval.17)

There are no sinter plants in operation in Sweden. In-plant fines are mainly recycled as cold bonded agglomerates. The BF flue dust used in the agglomerates has a negative effect on the briquette quality. On the other hand, this material is composed of fines from the materials originally charged into the BF and it contains valuable amounts of carbon and iron oxides that can be used in the BF. By injecting the flue dust into the BF, it will be possible to recover these valuable compounds without deteriorating the briquette quality.

Studies on the effects of injection of iron oxides are reported in the literature. In a study made by Kushima et al., on the injection of iron ore fines into the Hirohata No. 3 BF, the effect of particle size was estimated based on heat transfer calculation. Sinter fines with a mean particle size of ~2 mm were estimated to reach a temperature of ~500°C at the end of the raceway and it was concluded that the reduction reaction rate probably is very slow. Fine ore particles, 0.05 mm in diameter, were estimated to reach a temperature of 1500°C or more 0.4 m from the tuyere nose.
These particles will melt, follow the ascending gas, be adsorbed on the coke surface and undergo melting reduction. The average partial pressure of oxygen measured at the end of the raceway was $10^{-12}$ atm during normal BF operation, $10^{-11}$ atm, when pellet fines were injected and $10^{-9.3}$ atm, when sinter fines were injected. The measured oxygen partial pressure at the tuyere level almost corresponded to the FeO content of the slag sampled here. When iron ore fines were injected the blast moisture is decreased to compensate for the heat consumed by the iron oxides.\(^5\)

In a study by Yamagata et al. the injection of iron ore was made at Wakayama No. 4 BF without carryover of the injected ore to the hearth. In the laboratory, it was shown that FeO reacts with Si in the hot metal reducing the Si content of it. Coke of different particle sizes was added and FeO was directly reduced by coke and the consumption increased with a decreased particle size of coke because the contact surface between coke and slag increases.\(^6\) In other literature,\(^18\) it is stated that coal “char” is much more reactive than coke fines, so “char” is probably preferably consumed in the direct reduction with FeO. In practice, this means that if hematite is co-injected with coal the total efficiency of the use of coal may differ from the coal combustion efficiency in the raceway.

In a laboratory study by Kang et al. tests with simultaneous injection of coal char and fine iron ore oxide were made. The combustion gases from the injection furnace were analysed with a mass spectrometer and the residual material was quenched and studied after the test. The combustion rate of char increased with increased hematite/char ratio, which implies that hematite is an efficient oxygen source for char combustion. The reaction rate constant for char combustion was unchanged, when the ratio wustite/char was increased. This indicated that the injected hematite decomposes thermally into magnetite and oxygen and that the magnetite is directly reduced by the char. Injected wustite will be directly reduced by the char.\(^7\)

Laboratory tests by Gudenau et al. on simultaneous injection of PC and iron ore have been made with two types of coal with 5.6 and 30.0% of volatile matter (VM) respectively to which two types of iron ore, wustite and iron ore of coal with 5.6 and 30.0% of volatile matter (VM) respectively, have been tested in thermal analyses and high temperature XRD. Additionally, BF flue dust has been tested in thermal analyses and high temperature XRD.

2. Laboratory Study

2.1. Combustion Tests in Both a Fixed Bed Model and Blowpipe Model

2.1.1. Samples

The sample materials used in the tests are a high volatile (HV) coal, BOF slag and BF flue dust. The chemical compositions of the test materials are shown in Table 1. To produce material corresponding to 100, 75 and 60 µm, respectively, the original materials are screened. The chemical composition is quite similar for all fractions of BOF slag, but changes considerably for BF flue dust. The C content becomes lower and the Fe content higher, when the particle size is decreased. Typical C and Fe contents measured in a fractional analysis of BF flue dust produced at BF No. 3 in Luleå can be seen in Fig. 1. The BF flue dust is composed of a mixture of fines generated from the raw materials charged into the BF. The BF top works like a wind sieve and particles of certain fluidisation properties, dependent on the density, shape and size of the fines, will be carried out through the top with BF exhaust gas. As a result the BF flue dust recovered from the BF off-gas by a cyclone will contain a mixture of small iron oxide particles and coarser dust on the coal combustion efficiency, a laboratory study has been made in collaboration between SSAB Tunnplåt in Luleå, Sweden and the University of Science and Technology in Beijing, China. The effects of BOF slag and BF flue dust on the coal combustion efficiency with different adjustments of $O_2$ enrichment, temperature, amount of coal, amount of BOF slag or BF flue dust and particle size of BOF slag or BF flue dust have been studied. Thermal analyses have been made on coal and mixtures of coal and BOF slag or BF flue dust. Additionally, BF flue dust has been tested in thermal analyses and high temperature XRD.

### Table 1. Chemical compositions of the test materials, all values are given as (wt%).

<table>
<thead>
<tr>
<th>Coal</th>
<th>BF flue dust Original</th>
<th>BF flue dust &lt;100 µm</th>
<th>BF flue dust &lt;60 µm</th>
<th>BOF slag Original</th>
<th>BOF slag &lt;100 µm</th>
<th>BOF slag &lt;75 µm</th>
<th>BOF slag &lt;60 µm</th>
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</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0.28</td>
<td>0.32</td>
<td>0.32</td>
<td>0.28</td>
<td>0.36</td>
<td>0.36</td>
<td>0.32</td>
</tr>
<tr>
<td>CaO</td>
<td>0.25</td>
<td>0.42</td>
<td>0.42</td>
<td>0.25</td>
<td>0.36</td>
<td>0.36</td>
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</tr>
<tr>
<td>MgO</td>
<td>0.18</td>
<td>0.38</td>
<td>0.38</td>
<td>0.18</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>3.65</td>
<td>3.96</td>
<td>3.96</td>
<td>3.65</td>
<td>3.96</td>
<td>3.96</td>
<td>3.96</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>1.32</td>
<td>1.34</td>
<td>1.34</td>
<td>1.32</td>
<td>1.34</td>
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<tr>
<td>TiO$_2$</td>
<td>0.05</td>
<td>0.09</td>
<td>0.09</td>
<td>0.05</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>V$_2$O$_5$</td>
<td>0.01</td>
<td>0.07</td>
<td>0.07</td>
<td>0.01</td>
<td>0.07</td>
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</tr>
<tr>
<td>K$_2$O</td>
<td>0.14</td>
<td>0.13</td>
<td>0.13</td>
<td>0.14</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>MnO</td>
<td>0.004</td>
<td>0.04</td>
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<td>0.004</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>C</td>
<td>77.0</td>
<td>21.2</td>
<td>21.2</td>
<td>77.0</td>
<td>21.2</td>
<td>21.2</td>
<td>21.2</td>
</tr>
<tr>
<td>S</td>
<td>0.81</td>
<td>0.19</td>
<td>0.19</td>
<td>0.81</td>
<td>0.19</td>
<td>0.19</td>
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</tr>
<tr>
<td>LOI</td>
<td>24.3</td>
<td>11.1</td>
<td>11.1</td>
<td>24.3</td>
<td>11.1</td>
<td>11.1</td>
<td>11.1</td>
</tr>
<tr>
<td>Ash</td>
<td>1.8</td>
<td>2.3</td>
<td>2.3</td>
<td>1.8</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Fig. 1. Content of Fe and C in each fraction of BF flue dust.
coke particles. However, the chemical compositions are quite similar for the two fractions used in the combustion tests. Fe in the BOF slag is present as Fe_{met}, calcium ferrites and wustite containing MgO and MnO. In BF flue dust, Fe is present mainly as hematite, but also as magnetite.

2.1.2. Test Conditions

The aim of the combustion tests is to evaluate the influence of BOF slag and BF flue dust under different test conditions, e.g., temperature, oxygen enrichment, amount of PC, amount of BOF slag or BF flue dust and particle size of the BOF slag and BF flue dust. The combustion efficiency is measured both in a fixed bed model and in a blowpipe model. The amounts of coal and BOF slag or BF flue dust have been chosen to get ratios between coal and added material that are of the same range as in the pilot-scale and full-scale tests that have been carried out in blast furnaces. This means that 100 kg/tHM of PC and 15 kg/tHM of additive at the BF tests correspond to 0.200 g and 0.030 g in the fixed bed and 100 g and 15 g in the blow pipe model. The values corresponding to different levels of the factors are shown in Table 2. To decrease the number of tests, reduced test schedules based on these factors are used in all test series for combustion efficiency. The data are evaluated with a statistical computer software using multi linear regression (MLR). The explained variation (goodness of fit) of the test results is characterised by $R^2_{\text{adj}} = \frac{\text{MS}_{\text{residual}}}{\text{MS}_{\text{total corrected}}}$. $R^2_{\text{adj}}$ is always lower than $R^2 = \frac{\text{SS}_{\text{residual}}}{\text{SS}_{\text{total corrected}}}$ (SS = sum of squares) and less sensitive to the degrees of freedom. The predicted variation (goodness of prediction) of the model is characterised by $Q^2 = 1 - \frac{\text{SS}_{\text{predictive residual}}}{\text{SS}_{\text{total corrected}}}$. $Q^2$ can have a value between $-\infty$ and 1 and when $Q^2 > 0.5$ the predictive power is good, if $Q^2 > 0.9$ it is excellent. RSD given in the tables corresponds to the standard deviation of the residuals.

2.1.3 Fixed bed model

Figure 2 shows the fixed bed model chart. Coal and BOF slag or BF flue dust are mixed, weighed and transferred into a crucible. The sample is heated in air for 120 s in a muffle furnace pre-set to desired temperature. Finally, the sample is cooled in an inert atmosphere and weighed. The combustion efficiency of PC is calculated from the measured weight loss by using the following formula.

$$\eta = \frac{\Delta W}{W_m \times (1 - A_0)} \times 100 \%$$

where $\eta$: Combustion efficiency of PC (%), $W_m$: Weight of PC before test (g)

Table 2. Values corresponding to different factor levels in respective test series.
tion efficiency can be found in Table 4. The effects given correspond to the absolute effect on the combustion efficiency e.g. when the temperature is increased from min. to max. value, the combustion efficiency is increased by 10 percentage units. The confidence intervals show that all factors are significant, except for the particle size of BOF slag and BF flue dust. The values of $R^2_{adj}$ and $Q^2$ indicate good fitness and predictability of the regression model. In both test series, the results indicate that an increased temperature and a decreased amount of coal improve the combustion efficiency. The addition of BOF slag decreases the combustion efficiency, while the BF flue dust increases it. As can be seen in Table 4, the effect of temperature and coal amount are much higher in the test series with BF flue dust compared with the test series with BOF slag. This might be due to an interaction between two or more of the test parameters.

2.1.4 Blowpipe Model

Two test series are performed in the high-temperature blowpipe model. A schematic diagram of the test equipment can be seen in Fig. 3. A pulverised sample is injected for 120 s into the furnace and simultaneously mixed with preheated blast air and $O_2$, if it shall be added. The combusted sample is collected in water below the furnace and the ash content of the collected sample is analysed. The cross-designed test schedules used, which can be seen in Table 5, are based on the values of factors stated in Table 2. Three fractions of BOF slag and two fractions of BF flue dust are used. The ash content of each sample mixture is measured before and after the test. Based on these results the combustion efficiency was calculated using the formula

$$\eta = \frac{A_1 - A_0}{A_1(1 - A_0)}$$

where $\eta$: Combustion efficiency of PC (%)
$A_0$: The percentage of ash in the mixed sample before test
$A_1$: The percentage of ash in the mixed sample after test

The results obtained in each of the test series in the high-temperature blowpipe model can be seen in Table 5.
Sometimes a parameter, such as the particle size of BOF slag, deviates from linear increase/decrease, when the parameter level is changed and others can be influenced by the level of some other parameter. As can be seen in Fig. 4, the combustion efficiency reaches a minimum, when BOF slag of the intermediate particle size is used. Therefore, quadratic terms and interaction have to be used when estimating the effects on coal combustion efficiency.

Table 6 shows the effects on combustion efficiency for each parameter in the blowpipe model tests. (PSize=Particle size, BOF=BOF slag, BF=BF flue dust)

![Table 6. Effects on combustion efficiency for each parameter in the blowpipe model tests. (PSize=Particle size, BOF=BOF slag, BF=BF flue dust)](image)

In both test series, the main parameters i.e. the amount of BOF slag or BF flue dust, amount of coal, O2 enrichment and blast temperature have significant effects on the combustion efficiency. The combustion efficiency is decreased, when the amount of coal and the amount of BOF slag or BF flue dust are increased. The combustion efficiency is increased, when the blast temperature or O2 enrichment are increased. The particle size has a great effect in the test series with BOF slag, but has an insignificant effect in the test series with BF flue dust.

An example of when the effect of one parameter on the combustion efficiency is influenced by the level of another parameter is the amount of BOF slag. The combustion efficiency is almost unchanged, if the BOF slag added is of the fraction with <60 μm particles. The most negative effect on combustion efficiency is found with the intermediate fraction, <75 μm. Another example of this is O2 enrichment and temperature in the BF flue dust test series. An increased O2 enrichment increases the combustion efficiency in the test series at all levels of coal amount, when the temperature is at a low or intermediate level. At high temperatures, the increased O2 enrichment increases the combustion efficiency at the highest coal amount, but not at an-
termediate or low amount of coal.

2.2. DTA/TG Tests

2.2.1 Samples and Experimental Conditions

Thermal analyses are run using a Netzch STA 409 instrument for simultaneous Thermo Gravimetric (TG), Differential Thermal Analysis (DTA), and Mass Spectrometric (MS) measurements. Samples roughly 70 mg in mass contained in an alumina crucible are heated from room temperature to 1200°C, at a heating rate of 10°C/min in air atmosphere around the sample at a constant flow rate of 200 mL/min. Ar gas with a constant flow of 100 mL/min is supplied to the chamber. The samples are ground and mixed in a mortar. The chemical compositions of the pure materials are stated in Table 1. The samples with coal and BOF slag or BF flue dust are mixed in the proportion 5:1.

2.2.2 Results of DTA/TG

All samples tested with coal as the main component show in general similar behaviour and the properties of the high volatile coal will dominate the results. If the combustion degree is estimated based on the amount of combustible material in the sample, the combustibility of the samples is ~80%. The measured gas compositions during DTA/TG test for the three samples mixed with coal can be seen in Fig. 5. Moisture is released during the first part of the test coinciding with broad endothermic peaks. Chemical bound water is released and the content of H₂O in the gas has a peak in the temperature interval of 400–500°C. The CO₂ evolution starts at 250°C. At approximately 300°C, hydrocarbons (CHₓ, CₓHᵧ) are detected indicating that volatile matter is released. The maximum of the peak corresponding to H₂ occurs at ~600°C and this peak coincides with an endothermic peak. At ~600°C, the generation of CO₂ and H₂O is increased coinciding with a slightly decreased O₂ intensity. As can be seen in Fig. 6, the decreased O₂ intensity is especially significant in the samples containing BF flue dust. From 750°C until the end of the test, there is a CO₂ evolution. Small endothermic peaks around 1000°C coincide with an increased evolution of CO₂ in the samples of coal with BOF slag or BF flue dust added. No corresponding endothermic peak is detected in the sample with coal only. The rate of weight loss is quite similar during the whole test. The total weight losses for the tests are 76%, 61% and 67% for the samples with coal, coal and BOF slag and coal and BF flue dust, respectively. One sample of BF flue dust is also tested. The main results correlate with studies reported in the literature²⁰ and are summarised in Fig. 7. The O₂ content of the gas is lower during this test compared with the one during the other tests and CO is generated. Peaks corresponding to chemically bound water or hydrocarbons, which are found in all samples containing coal, are not detected in this sample and there is no weight loss below 500°C. Decomposition of carbonates occurs in the temperature range of 500–750°C coinciding with an endothermic peak and CO₂ evolution. The CO₂ generated reacts further with C producing CO that can be used for reduction of e.g. iron oxides resulting in a second peak of CO₂ coinciding with a narrow endothermic peak that is detected at approximately 800°C. When the temperature reaches 850°C the CO generation starts to increase and at ~950°C a large endothermic peak coinciding with CO₂ is detected.

BF flue dust is also analysed by XRD in air at elevated temperatures, see Fig. 8. Carbon, quartzite and hematite are detected in the original sample. The peak corresponding to carbon decreases between 440–750°C, however, the peak corresponding to carbon is quite small from 540°C. Peaks on the diffractogram measured at 850°C indicate wustite and Feₙmet and peaks on the diffractogram measured at 950°C indicate Feₙmet in addition to residual hematite and magnetite.
3. Discussion

3.1. Comparison of Conditions in Laboratory, Pilot-scale and Full-scale Tests

The amount of material used in the laboratory tests is small compared with that used in the BF tests. Based on the blast flow, the time for the gas to pass the raceway is estimated to \( <10 \text{ ms} \) at BF No. 3 and \( <5 \text{ ms} \) at the EBF. The time it takes for the gas to pass the furnace in the blowpipe model is 50–60 ms. In a 3D numerical simulation based on BF data, the average residence time of coal particles in the raceway was estimated to 29 ms. It was found that gas and coal particles recirculate in the raceway.\(^{21}\) The PC/Oxygen ratio (kg/Nm\(^3\)) is estimated to be 0.5 in EBF, 0.6 in BF No. 3 and 0.4 in the laboratory test for conditions corresponding to 4% O\(_2\) enrichment and 150 kg PC/tHM in the BF. In BF No. 3, an O\(_2\) enrichment of 4% is normal, but in the EBF tests the blast was enriched with approximately 2–3% O\(_2\). However, the O\(_2\) supply to each coal particle can be more affected by the lance design\(^{18,23,22}\) than by the amount of O\(_2\) supplied. In BF No. 3, a coaxial lance and at the EBF a oxy-coal lance of swirl type are used, both types improve the mixing between coal and O\(_2\), and in the laboratory equipment a tube is used.

In an actual BF, the residuals of injected coal reach the end of the raceway and can be used either in direct reductions reactions with e.g. FeO or take part in solution loss reaction. This will increase the efficiency of the use of coal. In the laboratory blowpipe model equipment the combusted sample is collected in water. In the fixed bed tests, these reactions may occur and consequently the combustion efficiency will be greater compared with in the blowpipe model tests, 62–63% and 48–49%, respectively. In Corus Netherlands (previous Hoogovens Ijmuiden), laboratory tests with injection through a full-scale blowpipe and tuyere into an empty furnace (size 2 \( \times \) 2 \( \times \) 6.5 m and with ambient pressure) gave a combustion efficiency of 65% for HV coal at a position 1 m and 10 ms from the tuyere nose (blast temperature 1 100°C). When the coal was injected into a furnace containing a void inside a coke bed with a temperature of 1 500°C, the combustion efficiency, as measured of the fines captured inside the coke bed and that of the fines leaving the coke bed, was increased to 80–90% at injection levels up to 200 kg/tHM.\(^{24}\)

The absolute value of the PC combustion efficiency achieved in the laboratory tests cannot be directly compared with an actual BF, but based on the analyses above it can be concluded that changed conditions in the laboratory tests increasing the combustion efficiency also can be expected to increase the combustion efficiency under BF conditions.

3.2. The Effect of BOF Slag on the Coal Combustion Efficiency

In the fixed bed test an increased temperature increases the combustion efficiency, but an increased coal amount or BOF slag amount decreases it. The combustion tests in the blowpipe model as well indicate that an increased tempera-
ture improves the combustion efficiency. O$_2$ enrichment increases the combustion efficiency also, but the effect of temperature is greater. The combustion efficiency measured in the blowpipe model is also decreased, when the amount of coal or BOF slag is increased. The coal combustion efficiency measured in the blowpipe model is almost unchanged with an increased addition of BOF slag, if the fraction $<60\,\mu$m is used. According to fractional analyses made of BOF slag, the chemical compositions of different fractions are quite similar. The considerably lower effect on the combustion efficiency found with an increased addition of BOF slag when using the fraction $<60\,\mu$m compared to when using BOF slag of fractions $<75\,\mu$m and $<100\,\mu$m may be explained by that the decreased particle size of the BOF slag is beneficial for fast heating and melting$^{22}$ and dispersion into the flow of coal. BOF slag particles in contact with the coal surface may be dissolved into the coal ash that is released, when the temperature is increased and the combustion starts. The melting properties of the tuyere slag will be significantly improved by dissolving BOF slag of a high basicity into the ashes from coal and coke produced at combustion.$^{27}$ Further studies are necessary to explain the fact that the use of a fraction $<75\,\mu$m had most negative effect on the PC combustion efficiency both in fixed model and blowpipe model tests. One reason can be that the $<60\,\mu$m is reduced and evenly distributed among the coal particles and dissolved into coal ash on the surface of the coal particles. The $<75\,\mu$m is also reduced, but not so well dispersed and dissolved into the coal ash, which might cause the formation of a slag of a high melting point decreasing the reaction surface of the coal particles. The formation of a slag of high melting point may be avoided in the $<100\,\mu$m fraction because of un-complete reduction of the low porosity BOF slag particles.

As can be understood from the description of the test method of the blowpipe model, the combusted sample is collected in water. In a real BF, the injected material will reach the end of the raceway. According to the literature, FeO in the BOF slag may be directly reduced by “char” and coke fines and the total efficiency (combustion in the raceway and consumption of “char” by direct reduction at the end of the raceway) of the use of coal will be increased.$^{5,7}$ The “char” is consumed preferably to coke fines.$^{18}$ The combustion efficiency in the fixed bed tests is in general much higher compared to the one in the blowpipe model test, average combustion efficiencies are 48% and 56%, respectively. The difference might be explained by a longer time available for reaction in an air atmosphere. An increased temperature is most effective, when the combustion efficiency in the fixed bed shall be increased. The reduction of BOF slag is slow at low temperatures, but is significantly increased, when the reduction temperature is increased to 1 150°C in isothermal reduction tests, but final reduction occurs when softening and melting starts.$^{16}$ Some O$_2$ released from the BOF slag during reduction might be supplied for combustion of coal, but the reduced BOF slag that has a higher melting point than the original BOF slag might also limit the diffusion of O$_2$ in the fixed bed. In a XRD test with BOF slag and coke at elevated temperatures melt was indicated at the diffractogram measured at 1 250°C, but the melt resolidified because of formation of a slag mainly composed of di- and tri-calcium silicates, when the BOF slag is reduced. This is probably also the reason for the lower effect on combustion efficiency when increasing the temperature or the coal amount.

The thermal test with coal and BOF slag shows similar behaviour as with coal only, except for some indications of direct reduction producing CO$_2$ at around 1 000°C and a slightly lower weight loss during the test. Considering the effect when co-injecting coal and BOF slag into the BF, this will reduce the flame temperature slightly. On the other hand, several studies have indicated a decreased activity of SiO$_2$ in the tuyere slag and therefore a decreased SiO(g) generation when injecting basic components. The SiO(g) generation as well includes endothermic reactions.

Pilot-scale tests performed at the LKAB experimental blast furnace with injection of BOF slag up to an amount of 36 kg/tHM resulted in an improved process stability and a decreased consumption of reducing agents.$^{10}$ Based on the results in this study, a decreased combustion efficiency could have been expected when BOF slag was co-injected with coal. The negative effects of a decreased combustion efficiency in the raceway can be counteracted by an improved permeability caused by the consumption of unburnt char and coke fines by FeO,$^{12}$ supplied by the BOF slag. The improved melting properties of tuyere slag$^{22}$ can as well be expected to improve the permeability. The mixture of BOF slag and high volatile coal will have a lower volatile content compared to coal only, which will have an effect on the ignition of coal. The increased basicity of tuyere slag will decrease the activity of SiO$_2$ in the slag followed by a decreased SiO(g) generation and Si content of hot metal$^{11–13}$ and therefore a decreased consumption of reducing agents.

### 3.3. The Effect of BF Flue Dust on the Coal Combustion Efficiency

The combustion tests in the blowpipe model indicate that an increased temperature and O$_2$ enrichment increase the combustion efficiency. The combustion efficiency is decreased, when the amount of coal or BF flue dust is increased. The particle size of BF flue dust has no significant influence on the combustion efficiency. The particle size of both fractions of the BF flue dust tested is small enough for fast heating to temperatures at which the hematite is reduced and the limestone calcinated. The fractionated analyses of the BF flue dust showed that the iron is predominant in the finer fractions and it is possible that the particle size is almost similar in the two fractions tested. The decreased positive effect of an increased O$_2$ enrichment on the combustion efficiency at elevated temperatures can be caused by an increased reduction rate and/or thermal decomposition of hematite at high temperature supplying O$_2$ for combustion of coal.$^{5–11}$ By increasing the temperature or O$_2$ enrichment and decreasing the amount of coal the combustion efficiency can be maintained, when BF flue dust addition is made. At high temperatures the O$_2$ enrichment increases the combustion efficiency only at the highest coal amount. An increased O$_2$ enrichment enhances the diffusion of O$_2$, but decreases the volume of the combustion gas that transfers heat to the PC. At the highest coal amount, the diffusion of O$_2$ might be the main factor that limits the combus-
tion rate.

According to the literature, the hematite in the BF flue dust can be partly reduced or decomposed in the raceway.\(^5\) Magnetite or wustite is directly reduced with “char” and coke fines e.g. at the raceway end and the total use of the injected coal is thereby increased. In the blowpipe model, the sample is collected in water and the direct reduction reaction cannot occur. The combustion efficiency is in general much higher in the fixed bed tests compared to that one in the blowpipe model test, 63% and 49%, respectively. An increased combustion efficiency in the fixed bed tests can be caused partly by the increased time available for reaction and partly by increased contact surfaces between coal and BF flue dust increasing the supply of O\(_2\) from hematite for combustion of coal. In the blowpipe model, O\(_2\) can be supplied from hematite, when it is reduced with CO or thermally decomposed. In the fixed bed tests direct reduction with C can additionally occur. In the literature, it is stated that in laboratory tests the combustion efficiency of “char” was improved with an increased ratio of hematite/char.\(^7\) The different effects of BF flue dust and BOF slag when added to the coal in the fixed bed tests might be caused by the calcination of limestone and the direct reduction of hematite starting at a low temperature according to the thermal analysis. CO\(_2\) released can react with C producing CO. The high basicity slag with a high melting point formed when BOF slag is reduced is not formed when BF flue dust is used. A small endothermic peak at 800°C and CO generation during the thermal test shown in Fig. 7 coincides with the reduction with wustite and Fe\(_{\text{total}}\) detected with high temperature XRD shown in Fig. 8. The XRD pattern in Fig. 8 indicates that the reduction proceeds further between 850–950°C. Reduction of iron oxides in BF flue dust at a quite low temperature and calcination reactions in BF flue dust and the reduction reaction will consume energy at the same temperature range as the volatilisation of coal occurs. Therefore, the effects on the combustion efficiency by an increased temperature and an increased coal amount will be higher when BF flue dust is added compared to when BOF slag is used. Reduction and calcination are enhanced by an increased temperature. The reactions supply O\(_2\) and CO\(_2\) that can be used for oxidation of C contained in PC.

Pilot-scale tests performed at the LKAB experimental blast furnace with injection of BF flue dust up to an amount of 30 kg/tHM together with PCI resulted in an improved process stability, a decreased Si content of hot metal and a decreased fuel consumption.\(^10\) Full-scale tests, on all 32 tuyeres, with a controlled addition of BF flue dust up to 15 kg/tHM, at SSAB in Luleå indicated good performance concerning process stability. The decreased combustion efficiency measured in the laboratory tests when BF flue dust was added can be expected to occur also under BF condition. However, the negative effects on the BF operation that could be expected by a decreased combustion efficiency of coal are counteracted by the consumption of “char” and coke fines by FeO in the raceway slag\(^6,12,18\) giving a higher efficiency of the total use of coal. The consumption of “char” and coke fines and the decreased melting point of tuyere slag because of an increased FeO content will improve the permeability in the raceway end and is probably the main cause to a decreased heat load and an improved S distribution in the full-scale test. The mixture of BF flue dust and high volatile coal will have a lower volatile content compared to the coal only.

4. Conclusions

Injection of BOF slag into a BF to improve the slag formation and of BF flue dust to improve the recycling of inplant fines has previously been tested. In this laboratory study, the effects on combustion efficiency at different combustion conditions, when these materials are co-injected with coal, are evaluated. Combustion efficiencies at varied temperature, O\(_2\) enrichment, amount of PC, amount of added BOF slag or BF flue dust and particle size of the added material are measured in a fixed bed and a blowpipe model. The established facts that an increased temperature and O\(_2\) enrichment or a decreased amount of coal increase the combustion efficiency are valid also when BOF slag or BF flue dust are added to the coal. By adjusting these parameters, a decreased combustion efficiency, when BOF slag or BF flue dust is added, can be counteracted. The general higher combustion efficiency in the fixed model compared with that one in the blowpipe model could be compared with the difference in combustion efficiency, when considering only the raceway or both the raceway and the coke bed at the raceway end.

The combustion efficiency is decreased, when BOF slag is added to the PC in the fixed bed or in the blowpipe model tests. By using BOF slag of a fine fraction, the combustion efficiency is almost unchanged in the blowpipe model. In the BF, the positive effect on the melting properties of tuyere slag resulting in an increased permeability in the raceway end and a decreased SiO(g) generation, will predominate the effects on the BF operation results.

In the blowpipe model tests, the expected O\(_2\) supply from hematite in the BF flue dust did not improve the combustion efficiency. The combustion efficiency is increased, when the supply of O\(_2\) from hematite is enhanced because of the increased time available for reaction and the improved contact between coal and BF flue dust allowing direct reduction with C as in the fixed bed. In the BF, the consumption of unburnt char and coke fines and the positive effect on the melting properties of tuyere slag that improve the permeability will predominate the effect on the BF operation result.

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