In the blast furnace process, material losses are caused by particles that are blown out of the furnace by the off-gas. In order to reduce these losses, it is important to understand the correlations between furnace conditions and off-gas dust formation. Off-gas dust, as flue dust and sludge, were collected during shaft probe sampling in LKAB Experimental Blast Furnace (EBF). Process data was used to evaluate the relationship between off-gas dust amounts and furnace conditions. The graphitization degree ($L_c$ value) of shaft coke and coke in flue dust was determined using XRD measurements. Solution loss in the shaft had a negligible effect on coke degradation and the coke particles which ended up in the flue dust were mainly derived from abrasion at low temperatures. The amount of alkali and SiO$_2$ in sludge increased with higher PCR and flame temperature, which confirmed that submicron spherical particles in sludge originated from the high temperature area around the raceway. Theoretical critical particle diameters of materials, which could be blown out with the off-gas, were estimated. Flow conditions in the top of the shaft as well as and the properties of fine particles in terms of size and density are important when outflow of mechanical dust, such as flue dust, is concerned. Low off-gas temperatures, and thus lower off-gas velocities, are favourable for low flue dust amounts expelled from the blast furnace.

**KEY WORDS:** blast furnace; off-gas dust; flue dust; sludge; pellet; sinter; coke.

### 1. Introduction

In the blast furnace process, material losses are caused by particles that are blown out of the furnace by the off-gas. In order to reduce these losses, it is important to understand the correlations between furnace conditions and off-gas dust formation.

Samples taken from the burden surface during a stoppage of a blast furnace operating with 100% olivine pellet as the iron-bearing material showed that the main component was carbon.$^{11}$ The particles were in the size range 0.25–2.0 mm and were assumed to consist of coke fines. It was suggested that the particles had been lifted up by the furnace gas and then redeposited on the burden surface as the gas velocity decreased above the burden surface. Similar results were obtained by investigation of fines deposited in the central area of the stock during shut down of Nagoya No. 1 blast furnace.$^{12}$ The results showed that more than 90% consisted of coke fines and less than 10% of sinter. Coke fines originated either from disintegration during charging or resulted from the solution loss reaction in the lower part of the shaft where fines were blown to the furnace top. Sinter was either unreduced or reduced to magnetite. The particle size distribution showed that approximately 25% of the material was finer than 0.5 mm. Gupta et al.$^3$ studied coke at high temperatures and its influence on coke fines in the blast furnace dust from three different blast furnaces. Thermal annealing tests in a laboratory furnace were performed with corresponding coke at from 1 000 to 1 600°C. Average crystallite height of coke carbon ($L_c$) was calculated and dust samples were divided according to three possible zones of origin in the blast furnace:

1. Upper parts including lumpy, softening and thermal reserve zones, <1 200°C
2. Middle part including cohesive zone, 1 200 to 1 400°C
3. Lower part below cohesive zone, >1 400°C

No coke fines from the third zone were found in any of the blast furnaces, which means that coke fines generated in this part stayed or were consumed inside the blast furnace. In two blast furnaces, dust samples originated from zone 2, while one blast furnace dust was derived from zone 1. The latter case could be attributed to coke properties, which have a greater impact on fines generation in the blast furnace upper regions, such as insufficient coke strength at lower temperatures. Coke in dust from the other two blast furnaces is claimed to be related to coke properties at higher temperatures, such as the graphitization behaviour. However, the blast furnace conditions have not been taken into account.

Segregation and accumulation of sintered ore and coke
fines have been investigated in a two-dimensional cold model by Kawai et al. Fine particles of sintered ore accumulated at different positions in the bed depending on their charging position. At both peripheral and middle charging, fines accumulated at peripheral positions in the lower part of the bed forced the gas through the central part of the bed. Peripheral gas flow was obtained after central charging of fines which accumulated in the upper central parts of the shaft. Fine coke particles charged with a uniform thickness descended with the bed in a fluidized state and went ahead of the coarser particles when the superficial gas velocity was lower than the critical velocity for fine coke particles to move up. It was concluded that the behaviour of coke fines with low density was significantly dependent on the gas velocity.

Comparison of specific types of pellets and sinter for use as blast furnace burden showed that sinter possessed high reducibility, but on the other hand wide size range and high reduction degradation. This pellet type showed low reduction degradation but a slower reduction. Therefore, it is likely that the different particle sizes of different iron-bearing material as well as expected differences in degradation behaviour will influence the ascending gas flow due to the location of generated fines.

Earlier studies by Sterneleand et al. involving flue dust generation during olivine pellet operation in the LKAB Experimental Blast Furnace (EBF) have shown generation of flue dust of 4.4–5.4 kg/tHM. It was believed that an improved gas distribution and a lowered off-gas velocity would result in less fine particles blown out of the furnace.

The gas flow of in-furnace gas and the off-gas are influenced if fines accumulate in the shaft. Areas with increased amounts of fines will decrease permeability and force the ascending gas in other directions, thus creating differences in gas velocity, possibly channeling in the burden and generation of off-gas dust. In order to maintain stable operation, but also to decrease material losses through off-gas, it is of importance to further understand in-furnace and off-gas properties in relation to dust generation. In the present study, off-gas dust and in-burden material were sampled during operation with different iron-bearing materials in the EBF. The accessibility to process data along with shaft material and off-gas dust provided opportunities to evaluate correlations between dust formation and furnace conditions. In part 2 of a two-part study, relations between process conditions and dust generation will be discussed, while the first part focused on characterization of off-gas dust and in-burden fines.

2. Experimental

2.1. EBF Tests

As mentioned in part one of the article series, olivine pellets were used as iron-bearing material in test periods 1–4 and a mixture of acid pellets and sinter in test periods 5–8. Quartzite at 26 kg/tHM, BOF-slag at 48–51 kg/tHM and limestone at about 42 kg/tHM, were used as slag formers during olivine pellet operation. In test periods 7–8, quartzite was added at a rate of about 43 kg/tHM. The blast flow rate was constant at 1 600 Nm³/h. During olivine pellet operation the pulverized coal injection rate (PCR) was in the range 147–156 kg/tHM and with sinter addition to the burden 133–139 kg/tHM. Table 1 shows an overview of test conditions in the EBF during a period of 4 h prior to off-gas dust and in-burden material sampling. Sampling was carried out when target conditions were reached in the different test periods. Coke quality parameters are shown in Table 2.

During olivine pellet operation, pellets were charged at an intermediate position and coke was divided at wall and centre positions. When sinter was added to the burden together with acid pellets, coke was charged in the centre and iron-bearing material at wall/intermediate positions. Figure 1 shows a schematic overview of the aiming point for layered charging of iron-bearing material and coke. The charging patterns were adjusted due to the choice of iron-bearing material to optimize the gas flow. When the off-gas temperature exceeded 290°C, water and nitrogen was sprayed above the burden surface to decrease the top temperature and protect the furnace equipment.

| Test period | Iron-bearing material | PCR (kg/tHM) | Flame temp. (°C) | Fuel rate (kg/tHM) | Limestone (kg/tHM) | Quartzite (kg/tHM) | BOF slag (kg/tHM) | Prod. rate (t/h) | Slag (kg/tHM) | Hot metal temp. (°C) |
|-------------|----------------------|--------------|-----------------|------------------|------------------|-------------------|------------------|----------------|--------------|------------------|
| 1           | Olefine pellets       | 156          | 2208            | 527              | 42               | 26                | 48               | 1.55           | 151          | 1454             |
| 2           | Olefine pellets       | 152          | 2219            | 522              | 42               | 26                | 48               | 1.51           | 151          | 1437             |
| 3           | Olefine pellets       | 147          | 2219            | 520              | 42               | 26                | 51               | 1.63           | 162          | 1417             |
| 4           | Olefine pellets       | 153          | 2085            | 521              | 42               | 26                | 51               | 1.58           | 157          | 1426             |
| 5           | 70% acid pellets & 30% sinter | 139          | 2247            | 533              |                  |                    | 1.59             | 117            | 1445             |
| 6           | 70% acid pellets & 30% sinter | 133          | 2248            | 526              |                  |                    | 1.60             | 118            | 1442             |
| 7           | 50% acid pellets & 70% sinter | 136          | 2252            | 526              | 43               |                    | 1.56             | 220            | 1432             |
| 8           | 50% acid pellets & 70% sinter | 133          | 2256            | 519              | 43               |                    | 1.56             | 218            | 1442             |

Table 1. Overview of test conditions in EBF during a period of 4 h prior to off-gas dust and in-burden material sampling. Materials sampled in test periods 1, 3, 5 and 7 were analysed in more detail.

Table 2. Coke quality parameters (%) during the test periods for coke produced by SSAB in Luleå.

| Micum 40 | Micum 10 | CSR | CRI |
|----------|----------|-----|-----|
| 80.2     | 8.0      | 72.9| 20.6|
2.2. Methods

2.2.1. Process Data

Process data from the EBF control system were used to evaluate the effect of some parameters on flue dust generation. Process data is logged every second and stored in a database as ten-second and minute averages. Data is then transferred to another database where process calculations are carried out for reports, trends and mass- and heat balances. Measurements of off-gas temperatures were taken in the uptakes. The off-gas composition measurements of CO, CO₂ and H₂ were taken after the dust catcher. Off-gas velocities were estimated based on heat and mass balances and geometrical data. Determination of sludge amounts per tonne of hot metal was based on solid content, pulp flow per unit of time and the production rate.

2.2.2. XRD Measurements

Coke from the shaft probes was evaluated by determining the coke graphitization degree, represented by the $L_c$ value. $L_c$ is calculated using Scherrer’s Eq. (1) on XRD measurements at the (002) carbon peak position:

$$L_c = \frac{0.89 \lambda}{\beta \cos \theta} \quad \text{(1)}$$

where $\lambda$ is the wavelength of the X-ray source, $\beta$ is the Full Width at Half Maximum (FWHM) of the 002 carbon peak and $\theta$ is the position of the 002 carbon peak. A sharper 002 peak gives a higher $L_c$ value and represents a higher degree of ordering in the carbon structure, and therefore a higher graphitization degree.

A copper Kα radiation (40 kV, 40 mA) was used as the X-ray source. Finely ground coke samples were packed into a plastic holder and scanned over an angular $2\theta$ range of 15–35° by using a step size of 0.050° and a step time of 8 s at each step. Flue dust samples with high C content were also evaluated.

2.2.3. Estimation of Critical Particle Diameter

Based on average off-gas temperatures and off-gas velocities during a period of 4 h prior to sampling, critical particle diameters for blow-out of in-furnace material have been calculated. In the calculations, particles were assumed to be spherical. The relationship between particle size and terminal velocity was, according to earlier studies:

$$U_t = \left[ \frac{4d_p(\rho_s - \rho_g)g}{3\rho_pC_D} \right]^{1/2} \quad \text{(2)}$$

where $U_t$ is the terminal velocity (m/s), $d_p$ is the diameter of particles (m), $\rho_s$ is the apparent density of particles (kg/m³), $\rho_g$ is the density of gas (kg/m³), $\rho_p$ is the density of particles (kg/m³) and $C_D$ is the coefficient of drag force (—). $Re_p$ is the Reynolds number for the particle (—):

$$C_D = \frac{4}{Re_p} \quad (Re_p < 0.4) \quad \text{(3)}$$

$$C_D = \frac{10}{Re_p^{1/2}} \quad (0.4 < Re_p < 500) \quad \text{(4)}$$

$$C_D = 0.43 \quad (500 < Re_p < 200,000) \quad \text{(5)}$$

3. Results

3.1. Furnace Conditions

Table 3 summarizes average off-gas properties during a period of 4 h prior to off-gas dust sampling in test periods 1–8. The off-gas velocities varied between 0.70–0.75 m/s for all test periods. Generally, the off-gas temperature was higher during operation with olivine pellets compared to operation with sinter addition to the burden. The lowest off-gas temperatures were observed during test periods 7 and 8 when 70% sinter and 30% acid pellets was used as the iron-bearing material. However, the differences were probably higher due to water and nitrogen spraying above the burden.

Average values of temperature measurements made with an over-burden cross probe during 1 h prior to off-gas sampling are shown in Fig. 2. Generally, the investigated periods with olivine pellet as the iron-bearing material showed

![Fig. 1. Schematic overview of the aiming point for layered charging of iron-bearing material (dotted grey) and coke (dotted black) indicated. 1. Divided coke charging applied in test periods 1–4. 2. Centre coke charging applied in test periods 5–8.](image)

| Test period | Iron-bearing material | Off-gas velocity (m/s) | Off-gas temp. (°C) | Off-gas CO (%) | Off-gas H₂ (%) |
|-------------|----------------------|-----------------------|-------------------|----------------|----------------|
| 1           | Olive pellets        | 0.74                  | 199               | 49.6           | 3.5            |
| 2           | Olive pellets        | 0.75                  | 208               | 47.8           | 3.4            |
| 3           | Olive pellets        | 0.73                  | 202               | 47.8           | 3.3            |
| 4           | Olive pellets        | 0.75                  | 202               | 47.8           | 3.4            |
| 5           | 70% acid pellets & 30% sinter | 0.73                  | 185               | 46.7           | 3.0            |
| 6           | 70% acid pellets & 30% sinter | 0.73                  | 195               | 46.9           | 3.0            |
| 7           | 30% acid pellets & 70% sinter | 0.70                  | 179               | 45.5           | 3.2            |
| 8           | 30% acid pellets & 70% sinter | 0.71                  | 179               | 45.4           | 3.2            |

Table 3. Overview of off-gas properties in the EBF during a period of 4 h prior to off-gas dust and in-burden material sampling.
larger variation in the over-burden cross temperature profile than periods with sinter as can be seen in Fig. 3. The figure also shows the average temperature of all the over-burden cross measuring points. Olivine pellet operation test periods showed lower over-burden probe temperatures compared to operation partly with sinter, due to a higher water and nitrogen spraying at test periods 1–4. However, the off-gas temperatures were higher in test periods with more variations in the over-burden cross probe temperatures and lower off-gas temperatures were observed for test periods with a somewhat flatter over-burden temperature profile and smaller variations.

Test periods 2 and 4 showed the highest average off-gas temperature and have high gas temperatures in the centre according to the over-burden cross probe measurements shown in Fig. 4. Despite this, the amount of flue dust in period 2 was in the same range as test periods 1 and 3, see Fig. 7.

Figure 5 shows horizontal temperature profiles at the position of the upper shaft probe for test periods 1, 3, 5 and 7. An increased temperature level was observed during operation with 70% acid pellets and 30% sinter as the iron-bearing material in test periods 5. Centre coke charging during test periods 5 and 7 showed lower $\eta_{CO}$ in the centre of the furnace compared to measurements taken during divided coke charging in test periods 1 and 3, see Fig. 6. The horizontal temperature profiles at the position of the lower shaft probe showed no differences due to the choice of charging positions or iron-bearing material in the investigated test periods.
3.2. Off-gas Dust

Off-gas dust generation as flue dust and sludge, shown in Fig. 7, was at approximately the same level during the investigated olivine pellet test periods, except for test period 4, when disturbances in the EBF process were observed some hours before sampling. Variations in flue dust generation were larger during test periods 5–8, but on a lower level than observed for test periods 1–3. Slightly higher sludge amounts were observed for test periods 1–4 than for periods 5–8.

Amounts of Fe, C and SiO\textsubscript{2} as kg/tHM in off-gas dust sampled in test periods 1, 3, 5 and 7, based on chemical analyses, are shown in Fig. 8. Fe and C amounts in flue dust and sludge were higher in samples from pellet test periods than from sinter periods. Alkali and SiO\textsubscript{2} amounts in sludge increased simultaneously, as seen by the relation in Fig. 9. The correlation between SiO\textsubscript{2} and PCR was less significant, see Fig. 9. However, the flame temperature, shown in Table 1, counteracted the influence of PCR in test periods 1, 6 and 8. Test period 1 had the highest PCR and the lowest flame temperature and test period 6 and 8 had the lowest PCR and the third and highest flame temperatures, respectively. Excluding these 3 periods, the $R^2$ value became 0.97.

Table 4 summarizes total charged amounts of Fe in ferrous material and coke per tonne of hot metal and losses in flue dust in test periods 1–8. Flue dust showed Fe amounts between 0.1 and 1.0 kg/tHM. Assuming that Fe in flue dust originated from the iron-bearing material, the Fe losses were at most 0.1%. Based on results in part 1 of this study, parts of the Fe content in flue dust generated during olivine pellet operation originated from BOF-slag used as slag former. Consequently, the actual losses of Fe from olivine pellets were less than presented in Table 4. According to the results in part 1 of this study, carbon in flue dust mainly came from coke particles. Under the assumption that all carbon in the present test periods originated from coke, 0.3–0.9% of charged coke was lost in the flue dust samples collected during test periods 1–4. In test periods 5–8, 0.04–0.2% of charged coke per tonne of hot metal ended up in flue dust. However, limestone was charged during test periods 1–4, which contributed to a minor part of the C content.

3.2.1. Estimation of Critical Particle Diameter

Based on average off-gas properties during a period of 4 h prior to sampling, critical particle diameters for blow-out of in-furnace material have been calculated.

| Test period | Fe in iron-bearing material (kg/tHM) | Fe in flue dust (kg/tHM) | % of Fe in flue dust | Coke rate (kg/tHM) | Coke in flue dust (kg/tHM) | % of coke in flue dust |
|-------------|-------------------------------------|-------------------------|---------------------|--------------------|--------------------------|-----------------------|
| 1           | 921                                 | 0.55                    | 0.06                | 371                | 1.7                      | 0.47                  |
| 2           | 921                                 | 0.94                    | 0.10                | 370                | 1.2                      | 0.33                  |
| 3           | 922                                 | 0.54                    | 0.06                | 373                | 2.0                      | 0.54                  |
| 4           | 922                                 | 0.94                    | 0.10                | 368                | 3.4                      | 0.93                  |
| 5           | 937                                 | 0.25                    | 0.03                | 394                | 0.5                      | 0.12                  |
| 6           | 937                                 | 0.45                    | 0.05                | 393                | 1.3                      | 0.32                  |
| 7           | 933                                 | 0.46                    | 0.05                | 390                | 0.8                      | 0.21                  |
| 8           | 933                                 | 0.09                    | 0.01                | 386                | 0.2                      | 0.04                  |
The Reₚ was calculated to be in the range of 1–13; hence, Eq. (4) is used for calculation of the coefficient of drag force, Cᵥ. Table 5 shows critical particle diameters estimated for different materials at average off-gas conditions.

From the theoretical calculations, iron oxides were expected to be found in fine flue dust fractions, while coke ought to constitute a major part of the coarser fractions. Characterization of flue dust in part 1 of this study has shown that Fe-containing material made up the major part of the <0.063 mm fraction and C-containing material the major part of >0.075 mm.

3.3. Material Distribution in the Shaft

3.3.1. Upper Shaft Probe Position

The material distributions of samples taken out with the upper shaft probe at estimated wall and centre positions are presented in Fig. 10 and Fig. 12. Ferrous material dominated in wall samples. Similar results were observed at estimated centre position with exceptions for test periods 2, 4 and 7, which showed a higher fraction of coke in the current samples. This could indicate that that probing was done in areas with larger coke particles or that the probe sub-sample 1 was closer to the EBF centre in these samples. In the investigated test periods, operation with sinter and acid pellets showed a higher amount of the 3.3–6.0 mm fraction compared to olivine pellet operation. Coke made up a larger part of the material at wall position when divided coke charging was applied during olivine pellet operation. Coke made up a larger part of the material at wall position when divided coke charging was applied during olivine pellet operation compared to centre coke charging when sinter was added to the burden. In wall samples, material in the 0.5–3.3 mm fraction was mostly made up of coke particles, as can be seen in Fig. 11. The fraction of 0.5–3.3 mm taken out at the wall position was highest during divided coke charging in olivine pellet operation.

3.3.2. Lower Shaft Probe Position

The material distributions of samples taken out with the lower shaft probe at estimated wall and centre positions are presented in Fig. 13 and Fig. 14. As in the upper shaft probe level, the coke fraction was higher in wall samples when divided coke charging was applied during olivine pellet operation compared to operation with centre coke charging under sinter addition to the burden. Coke dominated in centre position material in periods 2 and 5. A higher coke fraction in sub-sample 1 could depend on probing in the coke layer or targeting the actual centre of the EBF where coke predominates. Material in the size ranges 0.5–3.3 and 3.3–6.0 mm constituted an increased part of the material during operation with sinter compared to olivine pellet operation; an observation made independent of radial sampling position. The greatest amount of the <0.5 mm fraction was present at wall position during all test periods. In some sub-samples, aggregates of different materials and

Table 5. Estimated critical particle diameters of different materials in flue dust.

| Material      | Density (g/cm³) | Average conditions Dₚ (mm) |
|---------------|----------------|---------------------------|
| Hematite      | 5.10           | 0.055                     |
| Olivine pellet| 3.70           | 0.068                     |
| Sinter fines  | 4.50           | 0.090                     |
| Coke fines    | 1.95           | 0.105                     |
| Quartzite     | 2.77           | 0.093                     |
| Limestone     | 2.71           | 0.084                     |

Fig. 10. Material fractions in sub-sample X (X) (estimated wall position) taken out with the upper shaft probe in the EBF during test periods 1–8.

Fig. 11. Fraction of 0.5–3.3 mm material and Fe, SiO₂, CaO and C content in sub-sample X (X) (estimated wall position) taken out with the upper shaft probe in the EBF during test periods 1–8.

Fig. 12. Material fractions in sub-sample 1 (X) (estimated centre position) taken out with the upper shaft probe in the EBF during test periods 1–8.
3.4. Coke

3.4.1. Coke in the Shaft

The chemical analysis of coke ash in >6 mm coke taken out with the upper shaft probe is shown in Fig. 15 and from the lower shaft probe in Fig. 16, respectively. The total ash content is represented by the sum of oxides at the left axes. The ash content in upper probe coke samples was comparable to charged coke. The SiO$_2$/Al$_2$O$_3$ quotient was close to the value of 2.2 in charged coke, indicating no significant changes in coke at the level of upper shaft probe position.

At lower shaft probe position, a general increase in ash content occurred in coke from estimated intermediate/wall positions. In test period 1, an elevated SiO$_2$/Al$_2$O$_3$ ratio was observed at the same time as the alkali content was high. The second highest alkali content occurred in test period 5, although in this case the SiO$_2$/Al$_2$O$_3$ ratio was decreased, see Fig. 16.

Figure 17 illustrates the graphitization degree, represented by the $L_c$ value, of >6 mm coke at both upper and lower shaft probe positions together with some samples of flue dust. Generally, the $L_c$ values in coke from both upper and lower shaft probe corresponded to the $L_c$ values of charged coke. In test period 5, a higher graphitization degree was observed in the lower probe at estimated intermediate/wall and centre position, indicating a higher temperature than the coking temperature of approximately 1 100°C.

The intermediate/wall sample in test period 1 had an increased $L_c$ value at the lower shaft probe position.

LOM studies showed that coke in the 3.3–6.0 mm fraction taken out by the upper shaft probe generally showed no or small signs of coke gasification according to the solution loss or Boudouard reaction during olivine pellet operation test periods, see Fig. 18. In test periods 5 and 7, with 30 and 70% addition of sinter to acid pellet, respectively, a few areas in the coke texture were affected by the solution loss reaction. Coke in the 3.3–6.0 mm fraction originating from the lower shaft probe position showed some signs of coke gasification in the estimated intermediate/wall position of the EBF at test period 1, see arrows in Fig. 18, while the es-
segregation could cause a higher amount of fines near the sons for the increased amount of coke fines. One reason mainly made up of coke fines. There may be several rea-

creased, see Fig. 11, which showed that the material was 

The C content increased as the 0.5–3.3 mm fraction in-

divided coke charging compared to centre coke charging. 

Wall positions at the level of the upper shaft probe during 

0.5–3.3 mm material was observed in samples at estimated 

centre coke was mostly unaffected. In test period 5, 

signs of reacted coke textures were noted along the radius of the EBF. Test period 7 showed mostly un-reacted textures at lower shaft probe position.

3.4.2. Coke Fines in Flue Dust 

C content higher than 50 wt% allowed XRD measure-

ments directly on flue dust and were performed on the 

0.25–0.5 mm fraction from test periods 1, 3, 5 and 7, see 

Fig. 17. The $Lc$ values for test periods 3, 5 and 7 match the 

carbon crystal structure of charged coke. A higher graphitiza-

tion degree was obtained in test period 1, which indicated 

that coke fines were transported by the gas flow from an area below the lower shaft probe position. The coarser flue dust in the other test periods originated likely from coke in the upper part of the shaft. In olivine test period 3, the finer flue dust fraction of 0.063–0.075 mm showed the highest $Lc$ value of all samples, indicating origin from the high-temperature zone in the EBF.

4. Discussion

4.1. Distribution of Fines in the Shaft 

Differences in charging positions for raw material influ-

enced the material distribution in the shaft. Divided coke charging was applied during olivine pellet operation, while coke was charged at centre position when sinter was added to the burden. The higher coke content at wall positions through the shaft during olivine pellet operation was due to different coke charging positions. An increased fraction of 0.5–3.3 mm material was observed in samples at estimated wall positions at the level of the upper shaft probe during divided coke charging compared to centre coke charging. The C content increased as the 0.5–3.3 mm fraction increased, see Fig. 11, which showed that the material was mainly made up of coke fines. There may be several rea-

sons for the increased amount of coke fines. One reason could be the distribution of coke during charging, where segregation could cause a higher amount of fines near the wall. This phenomenon could have been less significant with centre charging of the EBF due to higher gas flow lifting the fine particles upwards. Another reason could be a combined effect of charging pattern and burden material used. Coke may have been degraded by abrasion, with high-density ferrous material pushing the coke towards the wall of the EBF during divided coke charging. Another possible explanation for coke surface breakage could have been that pellets, due to the spherical shape, were more movable than sinter and created abrasion when charged on top of coke layers and during the burden decent. However, this matter requires further investigation.

At the position of the upper shaft probe, measurement of $\eta_{CO}$, see Fig. 6, corresponded with the difference in charging pattern. Centre coke charging caused lower gas utilization in the centre of the EBF, which was evident for the test periods with sinter addition, and higher $\eta_{CO}$ at the wall where the ferrous material fraction was higher. Divided coke charging resulted in a flat gas utilization profile along the EBF radius. The presence of 0.5–3.3 mm fines at the level of the upper shaft probe will influence the gas distribution in the upper part of the shaft. It is thus possible that operation with divided coke charging forces the ascending gas to the centre of the furnace due to the accumulated 0.5–3.3 mm material at peripheral positions, which is in agreement with laboratory studies by Kawai et al. The radial distribution of 0.5–3.3 mm fines was more or less uniform during centre coke charging. The positions for coke charging were less significant for the radial distribution of 0.5–6.0 mm fines as material descended in the shaft.

Generally, there were more fines trapped in the burden during test periods 5–8 and more fines expelled through the top as flue dust during test periods 1–4. Samples from sinter test periods 5–8 had a higher fraction of 3.3–6.0 mm in both upper and lower shaft probe positions along the blast furnace radius compared to samples from olivine pellet test periods 1–4. The result indicated differences in particle size distribution of the charged material and/or differences in degradation properties. The fraction of $<0.5$ mm in sub-
samples taken out with the shaft probes increased towards the wall as well as from the upper to the lower shaft probe position. Results from the present investigation showed material fractions $<0.5$ mm to be independent of charging positions of raw materials and choice of iron-bearing material.

4.2. Coke 

4.2.1. Coke in the Shaft 

The higher $Lc$ value of coke, see Fig. 17, taken out from the position of the lower shaft probe in test period 5 indicates that the temperature was higher than the coking temperature of 1 100°C. Judging by the temperatures measured at the upper shaft probe position and the hot metal temperature in Fig. 5 and Table 1, respectively, the heat level in the EBF was higher at the time of sampling in test period 5. The coke near the wall in lower probe position in test pe-

riod 1 also had a higher graphitization degree, while the es-

timated centre coke had not. This could indicate that a local channel of gas has been formed near the wall. Based on the $Lc$ values, the temperatures at lower shaft probe position have not exceeded 1 100°C at the time of sampling in test periods 3 and 7.
Solution loss reaction (C+CO₂⇌2CO) causes coke weakening in the blast furnace and normally starts around 900–1000°C. When alkali, iron phases and CaO are present the solution loss reaction is catalyzed. LOM studies showed that some small areas have been gasified by solution loss in the lower shaft probe intermediate/wall sample in test period 1, see Fig. 18. In this case, a higher temperature and a high uptake of alkali had a catalytic effect and was the probable reason for coke gasification. In test period 5, at the level of the upper shaft probe, signs of solution loss gasification were noted in Fig. 18. Several factors may explain why solution loss took place at this height in the EBF. The temperature in upper shaft probe measurements was relatively high. The shaft probes are water-cooled and the actual temperature could have been even higher than reported in Fig. 5, making it possible to reach solution loss reaction temperatures. However, most of the coke shaft samples seemed unaffected by the solution loss reaction and had similar SiO₂/Al₂O₃ quotient as charged coke. The coke used in the EBF test periods was of low reactivity (CRI 20.6%), which contributed to the results. A coke with lower reactivity shifts the solution loss reaction towards higher temperatures, which means that the zone for gaseous reduction of wustite is extended to a lower level in the blast furnace. A low reactivity of coke used in a previous study in the EBF was stated to be the reason that coke samples taken from the shaft probes were hardly affected by the solution loss reaction.13)

4.3. Off-gas Conditions in the EBF

Low off-gas temperatures and velocities together with an even gas flow at the burden surface are desirable to achieve low amounts of material losses in flue dust. Generally, the off-gas temperatures were lower during centre coke charging with sinter addition to the burden compared to divided coke charging and olivine pellet operation. Sterneland et al. suggested that the improvement in flue dust generation was believed to be caused in part by better gas distribution. A lower off-gas velocity was believed to result in less fine particles being blown out of the furnace, which agrees with the present results. However, even in test periods 1–3, the generated flue dust amounts were generally lower than previously reported amounts with pellet operation in the EBF.

In test period 4, when disturbances in the process, including a stoppage, occurred before sampling, the amount of off-gas dust was higher. Although the off-gas temperatures and gas flow above the burden surface were similar to test period 2, see Fig. 4, less off-gas dust was blown out of the EBF in test period 2. The higher amount of flue dust and sludge in test period 4 is believed to be caused by fines accumulation during process disturbances and therefore, more fines available to be blown out of the furnace top.

4.3.1. Flue Dust

The losses of Fe and coke from the charged raw material to flue dust were quite small, as can be seen in Table 4. In the studied tests, 0.1% and less of charged Fe was lost in flue dust. If all C in flue dust was assumed to derive from coke, the losses vary between 0.3–0.9% in samples from olivine pellet periods and only 0.04–0.2% for samples taken out during sinter addition test periods. The movement of ferrous material could, as previously mentioned, result in an increased abrasion of coke.

Based on average off-gas properties, the critical diameters of particles that could leave the EBF and end up in the generated flue dust were estimated and presented in Table 5. The calculations showed that the magnitude of critical particle diameters were in the size range of the actual flue dust particles, which were previously characterized in part 1. Due to differences in density, the critical diameters for unreduced iron-bearing materials were smaller compared to coke particles. Although iron oxides, mainly consisting of Fe₂O₃, were predominant in fractions <0.063 mm, occurrence of larger particles in fractions >0.075 mm were observed. In the actual furnace, variations in off-gas properties such as temperature, composition and velocity occurred, which affected the flue dust amounts.

4.3.2. Factors Influencing Critical Particle Diameter and Actual amount of Flue Dust

In the present tests, an off-gas velocity of about 2–4 times the average was required to carry an unreduced iron oxide particle in the size range 0.125–0.250 mm out of the furnace, under the assumption that off-gas composition and temperature were the same as for the average case. Coke particles were, according to the characterization, commonly occurring in the coarser flue dust fractions. An off-gas ve-
locity of about 4 times the average velocity was, according to the calculations, required to allow a 0.5 mm coke particle to leave the furnace and end up in the flue dust when other off-gas properties were estimated to resemble the average case.

Formation of channels in the shaft will increase the gas flow in a particular area and an increased gas velocity would make it possible for particles of a larger size than the critical diameters to leave the furnace and end up in the flue dust. An indication of a local channel with increased gas velocity occurred during sampling in test period 1 when coke in flue dust fraction 0.25–0.5 mm showed elevated graphitization degree, indicating an origin below the lower shaft probe in the EBF.

Water was sprayed above the burden surface when the off-gas temperature exceeded 290°C. When vaporized, the added water could increase the off-gas volume as much as approximately 20%. Thus, the off-gas velocity increased and larger particles were allowed to be carried out by the off-gas. Prior to water spraying above the burden, higher off-gas temperatures were attained, which also facilitated outflow of larger particles.

According to the calculations of the coefficient of drag force, $C_D$, a higher drag force is obtained at increased off-gas temperatures. A lower Re value will increase $C_D$ and the critical particle diameters of material that can leave the EBF with the off-gas. In the present investigation, the highest amounts of flue dust were observed at the highest off-gas temperatures.

Geldart et al. showed that the carry-over rate of coarse particles in a fluidized bed increased when fine and coarse particles were mixed. Adding fines to the bed increased the carrying capacity of the gas, since the carry-over rate constant is directly proportional to the gas density. The terminal velocity of the coarser particles was reduced. A similar effect could occur in the EBF due to the presence of the spherical particles observed as sludge and in the shaft fines; hence, particles with a larger diameter than the calculated diameter could have been lifted by the off-gas.

4.3.3. Sludge

In part 1 of the articles it was concluded that sludge mainly contained spherical particles $<1 \mu m$ which were precipitated from the ascending gas as the temperature decreased. SiO$_2$ and MgO in sludge were derived from the high-temperature area of the EBF. Ökvist et al. stated that the composition and amount of the sludge were correlated mainly to the lower part of the blast furnace. Correlation between alkali and SiO$_2$ content in sludge indicated that an increase in SiO gas generation in the raceway area also increased the reduction and vaporization of K and Na, which are a part of silicates in coke and coal. Similar correlation was observed in the present investigation, see Fig. 9. The amounts in kg/tHM of sludge were slightly higher during sampling in olivine pellet periods compared to sinter periods. The PCR was also higher during olivine pellet operation, and a correlation between the amount of SiO$_2$ in the sludge and PCR was observed, see Fig. 9, supporting the hypothesis that the spherical particles in sludge originated from the high-temperature area around the raceway. Differences in the flame temperature counteracted the effect on SiO$_2$ content and PCR in three test periods. High flame temperatures increase the amount of SiO gas that is produced in the raceway area, and although the PCR was lower, the amount of SiO$_2$ in sludge was quite high. In test period 1, the PCR was high but a lower content of SiO$_2$ was noted due to a lower flame temperature.

The size of sludge particles was under all investigated test conditions much smaller than the majority of the particles in the shaft that were made up of ferrous material, coke and slag formers. According to previous studies, the largest diameter of a sphere that can pass through the smallest void of the bed densely packed with spherical particles is 0.155 times that of the spherical particle. In material sampled by the shaft probes, spherical particles $<1 \mu m$ were observed in the $<0.5$ mm fraction, however, the total samples were to the largest extent made up of coke, iron-bearing materials and slag formers in the range of $>6$ mm. Consequently, spherical submicron particles formed at any level in the furnace would have had the possibility to follow the ascending gas and exit the furnace.

4.4. EBF in Comparison to Industrial Blast Furnace

The EBF is operated in a similar way as a full-scale blast furnace and changes in operational parameters influence the process in the same direction as in the industrial case. Similar phenomena occur within the furnace, but the scaling effect may make them more or less pronounced. The EBF has proved to display similar behaviour as full-scale blast furnaces regarding the formation of the different zones within the blast furnace, the composition of the reducing gas and gas distribution over the radius. A faster response time after an operational change can be seen in the EBF and is caused by faster throughput of burden, shorter residence time of the ascending gas and the size of the coke reserve.

Some differences in the EBF when compared to an industrial blast furnace are the higher total consumption of coal and coke due to higher heat losses per tonne of hot metal and the higher silicon content in hot metal. Quartzite has to be charged in order to reach the desired slag volume when the Si content of the hot metal is quite high. In the EBF, there is a high ratio of raceway area to cross section area compared to an industrial blast furnace where the raceway depth is much shorter than the blast furnace radius and the centre region is filled with “dead man” coke. In an industrial scale blast furnace, the larger central coke bed allows for a greater re-oxidation of gas components from the raceway, for example, oxidation of SiO in the gas phase as well as Si dissolved in the hot metal, to occur thereby giving a lower Si content in hot metal. Changes in the raceway parameters have a more pronounced effect on both hot metal quality and process. This contributes, for example, to a higher content of SiO$_2$ in generated sludge from the EBF compared to the blast furnace No. 3 at SSAB in Luleå.

In Swedish production blast furnaces operated with 100% pellets, the amount of off-gas dust is generally 3–4 times as high as during pellet operation in the EBF. Further studies, including effects of furnace size, on off-gas dust from production furnaces are required to establish the causes of these differences.
5. Conclusion

In the present study, off-gas dust and in-burden material were sampled during operation with different iron-bearing materials in the LKAB Experimental Blast Furnace (EBF). Relations between process conditions and dust generation have been investigated based on process data and material properties.

As concluded in Part 1 the predominant fraction of flue dust was observed in the <0.5 mm size fraction. Carbon-containing particles dominated in the fractions >0.075 mm and consisted of mainly coke from the shaft. Fe-containing particles, as Fe₂O₃, made up the major part of the fractions <0.063 mm and originated from the top of the shaft.

Flow conditions in the top of the shaft, as well as the properties of fine particles in terms of size and density, are important when outflow of mechanical dust, such as flue dust, is concerned. Theoretical analysis shows that off-gas velocities have the greatest impact on flue dust amount in off-gas. Based on off-gas properties such as temperature, composition and velocity, it is possible to estimate particle sizes of materials of different densities in flue dust. Low off-gas temperatures, and thus lower off-gas velocities, are favourable for low flue dust amounts expelled from the blast furnace.

The charging pattern of coke was adjusted depending on the iron-bearing material. The effect of charging pattern was noted on 0.5–3.3 mm coke fines and gas utilization at the upper shaft probe position. Material in the >0.5 mm size range did not leave the EBF with the off-gas, but influenced in-furnace conditions.

Solution loss in the shaft down to the lower probe position in the EBF has a minor effect on coke degradation and the coke particles which ended up in the flue dust were mainly derived from abrasion at low temperatures. However, the present investigations of the coke graphitization degree in flue dust showed that coke particles <0.075 mm could be transported from the shaft level below the lower probe position, particularly if channels occurred, and exit the furnace with the off-gas.

The amount of alkali and SiO₂ in sludge increased with higher PCR and flame temperature, which confirmed that submicron spherical particles in sludge originated from the high-temperature area around raceway, as was concluded in part one of this study.

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