Analysis and optimization of fume extraction from a ferromanganese furnace tapping operation

L. Els*, P. Cowx†, P. Smith*, and R. Nordhagen†
*Resonant Environmental Technologies, Pretoria, South Africa
†Eramet Norway, Sauda, Norway

Tapping operations at ferroalloy smelters generate a significant amount of fume. Effective capture of fumes is required to meet the obligations of environmental, as well as occupational, legislation.

A study was completed on an existing fume extraction system at a ferromanganese furnace tapping area. The area under consideration included the tap-hole, launder, and ladle area. The study consisted of site test work as well as computational fluid dynamics (CFD) modelling to identify and evaluate solutions.

Site test work and observations during furnace operation provided a baseline of system performance as well as input parameters for CFD modelling. Gas flow rates and energy contents from each extraction area were measured. Photographs and video footage were taken to evaluate areas of fume leakage.

The CFD study was firstly validated against site observations to ensure the accuracy of input parameters. Thereafter several modification concepts were modelled and suitable combinations were investigated to ensure robust solutions. The following concepts were considered:

- Air curtains
- Ladle hood aspect ratio and position
- Increase of ladle extraction volume
- Extension of the length of the tapping garage structure

The paper presents the results of a performance test on a working ferromanganese tapping area fume extraction system and the results of CFD modelling as compared to site test results. Upgrade options are evaluated and an integrated robust upgrade of the system described.

Keywords: Secondary fume, manganese, tapping, tap-hole extraction, design, hoods.

Introduction

Eramet Sauda operates two ferromanganese furnaces as well as a manganese oxygen refining (MOR) unit. Secondary fume emissions are generated at the tap-holes as well as post-tap-hole operations. The existing secondary fume capture system has good capacity, but fugitive emissions escape from the furnace building. A study was therefore commissioned to optimize and upgrade the capture system. The first part of the study focused on casting areas (Els et al., 2013).

The manganese oxides in these fumes are easily inhaled due to their small size. Health effects include the contraction of manganism and various lung disorders. The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a Threshold Limit Value (TLV) of 0.2 mg/m³ time-weighted average (TWA) for manganese and manganese oxides. Norwegian laws for respirable manganese dust have become more stringent since 2008 and must be within a limit of 0.1 mg/m³ as an 8-hour average (Arbeidstilsynet, n.d.; International Manganese Institute, n.d.).

Theoretical background

The most important parameter for the design of fume capture equipment in the tap-hole area is the amount of energy released by the hot metal to the air above the metal surface. The rate of energy loss from the hot metal determines how long the ladle will take to cool down, which occurs via several mechanisms:

- Radiation from the hot metal surface to surrounding objects (air is mostly transparent to radiation)
- Conduction to surrounding surfaces such as refractory bricks on the launder and the metal ladle
- Convection from the hot metal surface to air above it
Reactions between the metal and the air.

The convection and reaction energies report to the air above the hot metal. This energy release determines the size of the plume of fume-laden air that is generated and consequently has to be captured. In addition, some energy is released by the furnace due to gas emissions from the tap-hole, and this also reports to the fume extraction system. These mechanisms are briefly discussed below.

Natural convection

The majority of fume extraction systems are designed based on flow rates calculated from thermal updrafts or plumes (Goodfellow and Tahti, 2001) caused by convective heat transfer (Cengel and Ghajar, 2011). Convective heat is, however, not an accurate estimate of the energy generated at hot metal handling areas, as reactions between the hot metal and ambient air also generate energy (Els, Coetzee, and Vorster, 2010).

Reaction energy

Reaction energy mechanisms including oxidation-enhanced vapourization and mass transfer-limited vapourization were previously considered in Els et al., 2013). The energy generated from the oxidation of evaporated manganese to Mn₃O₄ can be assumed to contribute to the plume energy. The oxidation rate can be assumed to be proportional to the rate of manganese evaporation for oxygen partial pressures above 17 kPa (Lee and Kolbeinsen, 2005). The evaporation rate is limited by the mass transfer of manganese away from the metal surface, which may be enhanced by oxidation at higher oxygen concentrations (Dushman, 1949).

Tap-hole emissions

Depending on furnace operating conditions, a significant amount of fume can be released from the furnace through the tap-hole. The amount of fume released is highly variable and depends on a number of factors, including the pressure inside the furnace and conditions during tapping (Kadkhodabeigi, Tveit, and Berget, 2010). Due to the highly inconsistent nature of this fume source, an energy source was inserted into the model at the tap-hole to account for energy releases either by furnace pressure or any lancing operations.

Test results

Flow testing

Sauda has a dedicated emission system baghouse, the environmental filter, with three fans. The system is designed to extract from one point per fan at one time. An extensive test campaign was carried out at Sauda on the existing fume extraction system. The flow and energy were logged continuously at the inlets to the extraction fans and tests were performed close to the hoods during the various operations. The average test results of relevant extraction hoods at the tapping area are shown in Table I.

Table I. Summary of extraction system test results

<table>
<thead>
<tr>
<th>Test point</th>
<th>Velocity</th>
<th>Temp.</th>
<th>Volume flow</th>
<th>Mass flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m/s</td>
<td>°C</td>
<td>Am³/h</td>
<td>Nm³/h</td>
</tr>
<tr>
<td>11 A Tap-hole</td>
<td>36.0</td>
<td>30.0</td>
<td>57261</td>
<td>50413</td>
</tr>
<tr>
<td>11 A Launder</td>
<td>31.1</td>
<td>32.5</td>
<td>49497</td>
<td>43075</td>
</tr>
<tr>
<td>11 A Ladle</td>
<td>40.6</td>
<td>33.1</td>
<td>64618</td>
<td>56123</td>
</tr>
<tr>
<td>11 C Tap-hole</td>
<td>41.1</td>
<td>60.0</td>
<td>65419</td>
<td>52635</td>
</tr>
<tr>
<td>11 C Launder</td>
<td>38.8</td>
<td>30.0</td>
<td>61651</td>
<td>54455</td>
</tr>
<tr>
<td>11 C Ladle</td>
<td>36.0</td>
<td>30.0</td>
<td>57261</td>
<td>50413</td>
</tr>
<tr>
<td>12 A Ladle</td>
<td>26.3</td>
<td>34.1</td>
<td>34061</td>
<td>29989</td>
</tr>
<tr>
<td>12 C Ladle</td>
<td>32.3</td>
<td>60.4</td>
<td>41802</td>
<td>33688</td>
</tr>
<tr>
<td>12 Tapping total</td>
<td>29.9</td>
<td>43.0</td>
<td>142863</td>
<td>119307</td>
</tr>
</tbody>
</table>

Maximum short-term peak total energies of 2.6 MW were recorded for all three areas combined (tap-hole, launder, and ladle). An ambient temperature of 20°C as measured on site was used as the reference temperature for all energy calculations. A combination of traverses and continuous monitoring at the extraction points and continuous monitoring at the fans was used to determine the maximum energy values.
CFD modelling

CFD modelling was used to simulate the fume generated at the tap-hole, launder, and ladles and evaluate the capture efficiency of various extraction concepts. The simulations were run using FloEFD 11.3.0.

A number of limitations due to the computational resources and time constraints on the project were identified with the modelling technique used. These limitations are listed below:

- The level of mesh refinement was limited to between 1 million and 2 million cells. This was done to minimize the run time while still obtaining meaningful results.
- FloEFD utilizes only a k-ε turbulence model. This model is based on a 2D vortex assumption. The turbulence in this case is 3D. A more advanced turbulence model such as full-stress Reynolds would provide a better simulation of the flow development.
- A steady-state formulation has been used. Heat convection is inherently unsteady. While it was possible to use an unsteady formulation, during the verification process, it was concluded that the steady-state formulation would give satisfactory results to enable a conservative evaluation the capture efficiencies of the hoods.

In general, it has been found that this modelling method results in a conservative evaluation of the performance of hood designs.

A number of different modification concepts were investigated. Each concept was investigated separately. Suitable combinations of these concepts were investigated to ensure robust solutions. The following concepts were considered:

- Air curtains
- Ladle hood aspect ratio and position
- Increase of ladle extraction volume
- Extension of the length of the tapping garage structure.

CFD boundary conditions

In order to model the fume extraction at the tapping garage, a 3D model of the area was created. The model included the slag and metal ladles, the tapping garage itself, launder, and tap-hole. The tap-hole and ladle extraction hoods were included in the model. The ladles were modelled as if they were full of metal/slag.

To establish a base case a number of different parameter sets were run to find the best match with observations on site. While the overall maximum energy released was measured on site, it is not possible in practice to measure energy release from individual fume sources. The results of these analyses were compared to the measurements and visual evaluations on site: from these comparisons a final base case was established. Only the final base-case arrangement is discussed here. In order to account for the case where the second slag ladle is full, an additional heat source was added to the relevant configurations.

To model the fume from various sources, surface heat transfer sources were specified on the relevant geometry. These heat sources are shown in Figure 1. The heat fluxes used at these sources were based on the site test work. After analysing the data collected during the site testing campaign, the extraction from the different hoods was calculated. From this analysis the worst-case extraction was found and used in the simulation. The extraction points used in the model are given in Figure 2.

Apart from the base case parameters, parameters were also specified for an increase in the ladle hood extraction volume and fume generation from the second slag ladle (Figure 3). The increased extraction volume was based on the maximum flow velocity that could be extracted in practice from the existing ducting. The maximum duct velocity was taken as 36 m/s. This results in a maximum extraction mass flow of 18 kg/s from each of the extraction points.
Figure 1. Final base case surface heat transfer sources

Figure 2. Locations of extraction points

Figure 3. Additional heat source applied to second slag ladle
CFD results

The air curtains, ladle hood aspect ratio and position, and garage extension are discussed separately. The increase of the ladle extraction volume and extension of the garage structure are discussed under the ladle hood and extension sections.

Air curtain concepts

Various air curtain angles and widths were investigated. Runs were performed with various air curtain velocities to optimize the effect of the air curtain (Figure 4).

By collecting the mass flow, temperature and specific heat parameters at the faces of the extraction hoods the energy captured at each hood was calculated. This was compared to the input surface heat transfer to determine the capture efficiency. The results are shown in Table II.

Table II. Air curtain CFD results

<table>
<thead>
<tr>
<th>Air Curtain</th>
<th>Width (mm)</th>
<th>Velocity (m/s)</th>
<th>Mass Flow (kg/s)</th>
<th>Temperature (°C)</th>
<th>Cp (J/[kg.K])</th>
<th>Energy (kW)</th>
<th>Capture Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>0</td>
<td>0</td>
<td>117</td>
<td>1018</td>
<td>1777</td>
<td>11</td>
<td>73</td>
</tr>
<tr>
<td>Vertical Air Curtain</td>
<td>30</td>
<td>15</td>
<td>123</td>
<td>1018</td>
<td>1887</td>
<td>11</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>20</td>
<td>121</td>
<td>1018</td>
<td>1851</td>
<td>11</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>20</td>
<td>116</td>
<td>1016</td>
<td>1756</td>
<td>11</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15</td>
<td>116</td>
<td>1016</td>
<td>1756</td>
<td>11</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>118</td>
<td>1018</td>
<td>1795</td>
<td>11</td>
<td>77</td>
</tr>
<tr>
<td>15° Air Curtain</td>
<td>10</td>
<td>20</td>
<td>118</td>
<td>1017</td>
<td>1794</td>
<td>11</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>116</td>
<td>1017</td>
<td>1757</td>
<td>11</td>
<td>85</td>
</tr>
<tr>
<td>30° Air Curtain</td>
<td>10</td>
<td>20</td>
<td>116</td>
<td>1017</td>
<td>1757</td>
<td>11</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>118</td>
<td>1018</td>
<td>1795</td>
<td>11</td>
<td>77</td>
</tr>
</tbody>
</table>

As can be noted from the results, there are several possible successful configurations: a vertical, 15°, or 30° air curtain, all of 10 mm width with 10 m/s air velocity. Temperature plots through the middle of the tapping garage (range 20–50°C) are shown in Figure 5 for the base case, as well as unsuccessful arrangements, and in Figure 6 for the several
successful configurations. Fume is identified by the areas of higher temperature. Any leakage is highlighted by the red areas outside the garage structure.

![Figure 5. Base case and unsuccessful configurations for the air curtain](image1)

![Figure 6. Successful configurations for the air curtain](image2)

**Ladle hood aspect ratio and position concepts**

The effect of altering the aspect ratio and position of the ladle extraction point on the efficiency of the extraction was investigated (Figure 7). The existing hood size (750×750 mm) and position was compared to a more slender 1900×300 mm hood in the existing and front positions. A push-pull type arrangement was also tested using the 1900×300 mm hood positions. The results are summarized in Table III.
As can be noted from the results, there are two possible successful configurations: both use a rear extraction position, with an increased ladle extraction rate of 18 kg/s. The shape of the hood does not significantly impact on the extraction efficiency. Temperature plots through the middle of the tapping garage (range 20–50°C) are shown in Figure 8 for several cases. Fume is identified by the higher-temperature areas. Any leakage is highlighted by the red areas outside the garage structure.
Extension of tapping garage structure concepts

An option of extending the tapping garage was investigated. This would involve casting additional concrete, and ladles would have to be moved further along their rails to allow clear crane access. Two extension lengths were investigated: 2.0 m and 2.5 m (Figures 9 and 10).

As the extension results in the tapping garage covering the second slag ladle, additional heat input from the second slag ladle was considered. The situation where the second ladle emits as much fume as the first slag ladle was considered. The analysis assumes that second slag ladle is full.

In order to combine the effects of the air curtain, increased ladle extraction and garage extension, four combined configurations were run. For these configurations a 10 mm wide 10 m/s vertical air curtain was used. The results are summarized in Table IV.
Table IV. Garage extension CFD results

<table>
<thead>
<tr>
<th>Hood Width (mm)</th>
<th>Hood Length (mm)</th>
<th>Taphole Mass Flow (kg/s)</th>
<th>Taphole Temperature (°C)</th>
<th>Cp (J/(kg.K))</th>
<th>Energy (KW)</th>
<th>Ladle Mass Flow (kg/s)</th>
<th>Ladle Temperature (°C)</th>
<th>Cp (J/(kg.K))</th>
<th>Energy (KW)</th>
<th>Capture Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>750</td>
<td>750</td>
<td>18</td>
<td>113</td>
<td>1018</td>
<td>1741</td>
<td>11</td>
<td>76</td>
<td>1013</td>
<td>624</td>
</tr>
<tr>
<td>2m Extension No 2nd Slag Ladle Heat</td>
<td>750</td>
<td>750</td>
<td>18</td>
<td>106</td>
<td>1016</td>
<td>1579</td>
<td>18</td>
<td>67</td>
<td>1011</td>
<td>855</td>
</tr>
<tr>
<td>2m Extension with 2nd Slag Ladle Heat</td>
<td>750</td>
<td>750</td>
<td>18</td>
<td>113</td>
<td>1017</td>
<td>1702</td>
<td>18</td>
<td>65</td>
<td>1010</td>
<td>727</td>
</tr>
<tr>
<td>2.5m Extension with 2nd Slag Ladle Heat</td>
<td>750</td>
<td>750</td>
<td>18</td>
<td>118</td>
<td>1017</td>
<td>1794</td>
<td>11</td>
<td>75</td>
<td>1012</td>
<td>612</td>
</tr>
<tr>
<td>2m Extension No 2nd Slag Ladle Heat 10mm@10m/s</td>
<td>750</td>
<td>750</td>
<td>18</td>
<td>118</td>
<td>1017</td>
<td>1794</td>
<td>11</td>
<td>76</td>
<td>1013</td>
<td>624</td>
</tr>
<tr>
<td>2m Extension with 2nd Slag Ladle Heat 10mm@10m/s</td>
<td>750</td>
<td>750</td>
<td>18</td>
<td>119</td>
<td>1017</td>
<td>1812</td>
<td>11</td>
<td>122</td>
<td>1019</td>
<td>1143</td>
</tr>
<tr>
<td>2m Extension with 2nd Slag Ladle Heat 10mm@10m/s</td>
<td>750</td>
<td>750</td>
<td>18</td>
<td>119</td>
<td>1017</td>
<td>1812</td>
<td>11</td>
<td>122</td>
<td>1019</td>
<td>1143</td>
</tr>
</tbody>
</table>

As can be noted from Table IV, the extension increases extraction efficiency. However, if the second slag ladle is filled up and emits fume (due to entrained metal), 100% efficiency is not achieved under any of the simulated conditions.

Figure 10. Garage extension CFD results (1)

Figure 11. Garage extension CFD results (2)
Discussion and conclusions

The base case simulation showed similar leakage patterns to those seen on site. Conclusions on specific concepts are as follows.

Air curtains

All the arrangements show that a thin lower velocity air curtain (10 mm at 10 m/s) is most effective in this application. Varying the angle of the air curtain between 0°, 15°, and 30° did not show any significant benefits.

The benefits of the lower velocity are twofold:

• The lower velocity results in the curtain flow being pulled in by the extraction draught. The higher velocity curtains are not overcome by the extraction draught and are deflected out of the garage by the slag ladle. In these cases the air curtain entrains fume which is lost when the flow is deflected.

• The air curtain flow needs to be extracted by the extraction points to ensure no leakage due to entrained fume. The lower velocity means that the air curtain volume flow rate is lower and hence has less effect on the extraction.

The benefit of the 10 mm air curtain over the 20 mm and 30 mm is the reduction in flow rate for similar velocity. Similar to the lower flow velocity, this reduces the additional volume that the extraction points have to handle. 10 mm has been taken as the smallest practical width.

Ladle hood aspect ratio and position

Two hood positions were considered: the current position and one close to the front of the tapping garage. The current 750×750 mm square offtake was also compared to a more slender 1900×300 mm design. Finally, a push curtain opposite the slender offtakes was considered.

The results showed that:

• The current position is more effective than the front position

• The slender hood aspect ratio showed a slight improvement over the current square arrangement

• The push curtains tests were found to be ineffective. The additional volume blown into the garage resulted in additional fume leakage

• Increasing the ladle hood extraction rate was shown to improve the capture significantly.

Extension of tapping garage

Two extension lengths were considered: 2.0 m and 2.5 m. By extending the garage, the second slag ladle becomes partly enclosed. This makes it practical to consider capturing fume from the second slag ladle as well. Heat from the second slag ladle was considered. The results showed that:

• The 2.0 m extension improved the capture efficiency over the base case

• A very slight improvement was seen between the 2.5 m and 2.0 m extensions

• In order to maximize capture the increased ladle hood extraction was necessary

• Neither extension could completely capture the second slag ladle fume.

Combination of 2.0 m garage extension, increased extraction, and air curtain

To be able to assess if the second slag fume could be captured under the simulated conditions, a 10 mm 10 m/s vertical air curtain was added to the extended garage model. The results showed that:

• With the air curtain both the 11 kg/s and 18 kg/s ladle extraction resulted in 100% capture under normal heat (no second slag ladle heat) conditions

• Neither the 11 kg/s nor 18 kg/s extractions could capture all the fume with the second slag ladle heat, even with the addition of an air curtain.

From the results of these analyses the following modifications have been highlighted as the most effective:

• 10 mm at10 m/s air curtain

• Increasing the ladle extraction rate to 18 kg/s

• Extending the garage structure.
References


