USING DATA-DRIVEN ANALYTICS TO DEVELOP A MATERIAL BALANCE OVER A FERROCHROME FURNACE

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ABSTRACT

Furnaces used for ferrochrome production are complex systems. There are a significant number of inlet and outlet streams with various parameters. However, some of these parameters are not always measured, which can limit decision-making abilities. Linking available data and additional information together with data analytics can possibly produce estimates of the unknown streams. It is, therefore, necessary to perform a material balance on a typical ferrochrome furnace to evaluate the underlying fundamentals of this concept. This paper provides a brief overview of the furnace parameters measured in practice, before presenting an approach to perform the material balance. The available measurements of input and output streams are used together with literature-based compositions. This analytical approach links the known composition together with the known mass to estimate the unknown streams. The analytics are structured in such a way that it can later be automated.

The approach is applied to several industrial case studies and the results are presented in order to provide a proof of concept. The analysis manages to balance all elements (in and out) within an accuracy margin of 1.25%. The results are further discussed to illustrate the potential benefit in various application areas.

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1. INTRODUCTION

Furnaces used for ferrochrome (FeCr) production are complex systems [1]. There are a significant number of inlet and outlet streams with various parameters [2]. However, due to difficulty (and in some cases financial restraints), some of these parameters are not always measured [3] which can limit decision-making abilities. Linking available data and additional information together with data analytics can possibly produce accurate estimates of the unknown streams. It is, therefore, necessary to perform a material balance on a typical ferrochrome furnace to evaluate the underlying fundamentals of this concept.

Section 2 of this paper will focus on research done on the FeCr production process as well as mass and composition measurements typically conducted at a furnace. Data quality analysis was also researched and summarised. The method to be followed for conducting a material balance over a typical FeCr furnace is described in Section 3. Even though every furnace is unique, generic steps and examples are provided. The methodology from Section 3 was applied to a real-life FeCr furnace and used as case study for this investigation. The results are provided and discussed in Section 4, while the paper is concluded in Section 5.

2. RESEARCH BACKGROUND

2.1 Ferrochrome production process

The process of FeCr production is an energy intensive one [4, 5]. The total electricity consumption of such a process typically ranges between 3.3 and 4.2 kWh/t of FeCr produced [6, 7, 8]. FeCr is mainly used for stainless steel production, where approximately 1 tonne is needed to produce 3 – 3.5 tonnes of stainless steel [9].

Production is accomplished by feeding raw materials in the form of chromite ores, carbon-rich materials (reductant such as anthracite, char, and coke), and additives (fluxes, in the form of quartz, limestone, dolomite, etc.) to an arc furnace [10, 11, 12]. In some cases, the raw materials are prepared before being fed to the furnace: pelletising, sintering, and drying techniques are often performed on raw materials to produce a dry and uniform feed to the furnace, which would increase furnace stability [13, 14].

Electricity is used to heat up the furnace and melt the raw materials by means of an electric arc [15, 16]. Due to the heat provided, various chemical reactions take place, causing reduction of the metal oxides within the chromite ore to a final metal product, FeCr. Together with the main metal product, waste material (slag) as well as off-gas also exit the furnace as by-products [17]. Figure 2-1 shows an illustration of this process [18].

![Figure 2-1: Ferrochrome production process](image-url)

For the purpose of simplification, this diagram has been summarised to establish the focus area of this study: FeCr furnace, input, and output streams. A simplified illustration of this process is thus shown in the diagram below (Figure 2-2).
As mentioned, various reactions take place within the furnace which cause the FeCr product to be formed. The most significant reactions included the following [1, 18, 17, 19]:

\[
\begin{align*}
\text{Cr}_2\text{O}_3 + 3\text{C} & \rightarrow 2\text{Cr} + 3\text{CO} & \text{Equation 2-1} \\
\text{FeO} + \text{C} & \rightarrow \text{Fe} + \text{CO} & \text{Equation 2-2} \\
\text{SiO}_2 + 2\text{C} & \rightarrow \text{Si} + 2\text{CO} & \text{Equation 2-3} \\
\text{H}_2\text{O} + \text{C} & \rightarrow \text{H}_2 + \text{CO} & \text{Equation 2-4} \\
\text{CO}_2 + \text{C} & \rightarrow 2\text{CO} & \text{Equation 2-5} \\
\text{CaCO}_3 & \rightarrow \text{CaO} + \text{CO}_2 & \text{Equation 2-6}
\end{align*}
\]

From these reactions it can be assumed that the prominent elements present within the FeCr furnace are the following: Cr, Fe, C, Si, O, H, and Ca.

2.2 Typical measurements

Not all parameters are always measured at ferroalloy furnaces [20]. Mass balances can be used to predict mass and compositions of certain unmeasured streams [14]. The measurements typically available for the general furnace will be discussed briefly.

FeCr metal product

The main objective of the process referred to within this study is the production of FeCr metal, with a certain alloy grade. The mass and composition of the metal produced is therefore monitored closely and measured continuously [20]. The metal is tapped a few times per day, solidified, crushed, and then weighed on weigh-bridges'. Metal samples are also sent for regular (usually daily) composition analysis. A typical composition of FeCr product is as follows: 56.7% Cr, 33.8% Fe, 7.2% C, and 2.3% Si [21].

Raw materials

The mass of raw materials (chromite ore, reductant, and fluxes) are usually measured at weigh bins before being batched to the furnace [22]. The composition, however, is rarely known on site. Occasionally sampling of the reductants takes place on site. However, this is generally done long before batching (before materials are stored on stockpiles) creating a significant buffer capacity. From literature, the composition of each of the raw materials normally used in FeCr production is summarised below:
Cr ore: 50% Cr$_2$O$_3$, 25% FeO, 9% MgO, 10% Al$_2$O$_3$, 5% SiO$_2$, 1% CaO [21]
Anthracite: 88.94% C, 3.4% H, 2.32% O, 1.55% N, 0.8% S [23]
Char: 77.84% C, 0.34% H, 21.11% O, 0.71% N [24]
Coke: 89% C, 3.6% H, 1.56% H, 4.95% S [25]
Dolomite: 100% CaMg(CO$_3$)$_2$ [26]
Limestone: 100% CaCO$_3$ [27]
Quartz: 100% SiO$_2$ [28]

**By-products**

The two by-products (slag and off-gas) have often been considered waste streams and are rarely measured accurately. The slag composition is, however, estimated to ensure the required slag composition [29]. From time to time, the slag mass is calculated by using a slag to metal ratio (usually between 1.1 and 1.8 tonnes of slag produced per tonnes of metal [30]), which is estimated by random sampling. The amount of slag produced can also be estimated based on an aluminium (Al$_2$O$_3$) balance. This is done with the assumption that the slag analysis is done accurately and representatively [31].

Then slag and off-gas compositions are given below:

**Slag:** 23.2% SiO$_2$, 24.7% Al$_2$O$_3$, 19.8% MgO, 3.0% CaO, 10.7% FeO, 18.6% Cr$_2$O$_3$ [31]
**Off-gas:** 75–90% CO, 2–10% CO$_2$, 2–15% H$_2$, 2–7% N$_2$ [2, 19]

The typical compositions are converted to element-based compositions by using the molecular weight of each formula and element. The results are summarised in Table 2-1:

**Table 2-1: Typical compositions for streams entering and exiting a FeCr furnace (element-based)**

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Cr</th>
<th>Si</th>
<th>S</th>
<th>C</th>
<th>Al</th>
<th>O</th>
<th>Ca</th>
<th>Mg</th>
<th>H</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>17.5</td>
<td>34.2</td>
<td>2.3</td>
<td>-</td>
<td>-</td>
<td>5.2</td>
<td>34.6</td>
<td>0.7</td>
<td>5.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.8</td>
<td>88.9</td>
<td>-</td>
<td>2.3</td>
<td>-</td>
<td>-</td>
<td>3.4</td>
<td>1.6</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>77.8</td>
<td>-</td>
<td>21.1</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
<td>0.7</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.0</td>
<td>89.0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>3.6</td>
<td>1.6</td>
</tr>
<tr>
<td>E</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>13.0</td>
<td>-</td>
<td>52.2</td>
<td>21.7</td>
<td>13.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>F</td>
<td>-</td>
<td>-</td>
<td>46.7</td>
<td>-</td>
<td>-</td>
<td>53</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12.0</td>
<td>-</td>
<td>48.0</td>
<td>40.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H</td>
<td>8.3</td>
<td>12.7</td>
<td>10.8</td>
<td>-</td>
<td>-</td>
<td>12.8</td>
<td>41.3</td>
<td>2.1</td>
<td>11.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>33.41</td>
<td>-</td>
<td>45-59</td>
<td>-</td>
<td>2-15</td>
<td>2-7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Chrome ore = A, anthracite = B, char = C, coke = D, dolomite = E, limestone = F, quartz = G, FeCr metal = H, slag = I, off-gas = J.

The typical mass ratio of input and output streams are as follows [17, 18]:
- 2.1 – 2.4 tonnes Cr ore fed per tonne FeCr metal produced
- 0.5 – 0.55 tonnes reductants fed per tonne FeCr metal produced
- 0.1 – 0.45 tonnes fluxes per tonne FeCr metal produced
- 1.1 – 1.3 tonnes slag per tonne FeCr metal produced
- 0.9 – 1.1 tonnes off-gas per tonne FeCr metal produced

The chromium recovery of this process is usually around 80% – 85% [18].
2.3 Data quality

Data quality is an important factor for a number of reasons and needs to be monitored pro-actively [32]. When evaluating a FeCr furnace, a significant amount of data needs to be collected, processed, and analysed. Therefore, thorough data evaluation is necessary.

A study done by Booysen [33] provided a data quality evaluation method that was developed to identify any potential errors and abnormalities. This method consists of four steps: the first three steps aim to identify abnormal measurements, whereas the final step identifies abnormal operation. A schematic flow of this method is shown in Figure 2-3.

![Figure 2-3: Data quality evaluation [33]](image)

Figure 2-3 provides a simplified visualisation of a dataset containing typical measurement abnormalities. The minimum and maximum limits are selected based on the variable being assessed. Steps 1 - 3 are indicated on this figure as follows: data spikes (step 1), faulty data (step 2), and data loss (step 3).

![Figure 2-4: Data evaluation - Identifying abnormal measurements](image)
The first step of identifying abnormal measurements within the data evaluation method, aims to detect data spikes. Data spikes happen when there is a failure on measurement equipment or when communication is briefly lost. Even though these tend to happen over short periods of time, their amplitude (very high or very low) can still significantly influence the accuracy of calculations.

The next step is to identify metering malfunctions, which could lead to faulty data being logged. This occurrence is illustrated as a constant value in Figure 2-4, where the last data reading is typically repeated for a number of resolutions, until the malfunction has been resolved. Even though this data will still fall within the operational limits, the results will be influenced by this incorrect, constant value.

Step 3 aims to identify data loss. This can generally be detected where no data has been recorded, as indicated by the blank space in Figure 2-4. The final step of this method aims to identify abnormal system operation. This is illustrated by Figure 2-5.

![Figure 2-5: Data evaluation - Identifying abnormal operation](image)

In Figure 2-5 there are numerous profiles that follow the same trend, indicating normal operation. The red profile however is deemed abnormal, as it differs from the trend. The utmost care should be taken when investigating these results as there is, unfortunately, no fixed rule as to what is defined as “abnormal operation”. This step therefore requires a thorough understanding of the process being evaluated.

The aim of this data quality evaluation method is to evaluate a dataset, remove any measurement abnormalities, and identify operational abnormalities. An accurate, high quality dataset is the final outcome of this method.

2.4 Research background conclusion

The research background section focused on the following:

- The basic process of FeCr production, so that all the theoretical components and elements are known to the reader.
- The typical setup and measurements, so that the reader can understand the practical implications and challenges faced when conducting a mass balance.
- Data quality, so that the practical data can be assessed to be usable before being included in the mass balance.

This was applied to develop a functional method on constructing a mass balance for a typical FeCr furnace.
3. METHODOLOGY

The methodology is divided into three main steps: Collect information, layouts, and data; evaluate data quality; and construct a material balance. An overview of this strategy is presented in Figure 3-1.

![Figure 3-1: Basic three-step methodology for developing a FeCr material balance](image)

This strategy provides the basic knowledge to developing a material balance, based on data-driven analytics. Each step is discussed in more detail in Sections 3.1 through 3.3.

3.1 Collect information, layouts, and data

The first step is to collect all relevant information from the site being evaluated. This includes layouts of the furnace, the relevant points of measurement indicated on layouts, as well as the corresponding mass and composition data for the evaluation period. Figure 3-2 indicates the outcome of this step. Note that for illustration purposes, only data collected for ferrochrome metal produced is shown on the layout (mass and composition data). However, data from all available streams must be collected.

![Figure 3-2: Collect information, layouts, and data](image)
The circles on the layout represent points of (required) measure. Green circles indicate that data is available, the orange represent data available, however not in the correct format, while the red circles indicate that data is not available, or not even measured. The “M” symbols refer to mass measurements (by means of weighbridges or weigh bins), whereas the “C” denotes composition analysis sampling taking place.

If data is to be required for an orange-indicated measurement point (data that is available, but not in the correct format), data needs to be processed to the correct analysis by making use of various assumptions or methods. An example of such a case is when the reductant composition is based on proximate analyses instead of ultimate analyses. The slag mass may also not be available, however, slag to metal ratio data can be used to calculate a theoretical slag mass.

3.2 Evaluate data quality
Having an accurate and “good” quality dataset is essential. It is important that all the data received in step 1 is a reflection of the truth. Step 2 of the methodology is thus to evaluate the data quality. The method provided in section 2.3 (Figure 2-3) needs to be followed for all mass and composition measurements in order to clean the dataset. This will ensure a representative, “good” quality dataset. Only then can the data be processed and used in further calculations.

3.3 Constructing a mass balance
A basic mass, or material balance is based on the principle of “mass in equals mass out” [34]. A material balance can be performed on the total mass entering and exiting the FeCr furnace, but also based on the individual chemical elements. These two different approaches are shown in Equation 3-1 and Equation 3-2, respectively:

\[
M_{\text{ore}} + M_{\text{reductant}} + M_{\text{flux}} = M_{\text{FeCr}} + M_{\text{slag}} + M_{\text{off-gas}} \quad \text{Equation 3-1}
\]
\[
\sum(M_{X_i}) = \sum(M_{X_{\text{out}}}) \quad \text{Equation 3-2}
\]

Where “M” represents the total mass of a certain stream or element, and “X” refers to a certain chemical element. Constructing a mass balance is the third and final step of the method, as referred to by Figure 3-1. This step will however take place over four different phases:

3.3.1 Calculate total mass of unmeasured streams
From the research section in 2.2, it is gathered that the mass of all batching streams (ore, reductant, and flux) are generally measured, as well as the mass of FeCr produced. Slag mass data is usually in the form of a ratio; however, it can be derived to estimate the total mass of slag. Thus, the only unknown stream mass is that of off-gas. By using Equation 3-1, the mass of the total off-gas stream can be calculated.

3.3.2 Assume the composition of all streams
Section 2.2 was summarised into Table 2-1 which provided the typical compositions for streams entering and exiting a FeCr furnace (element-based). This table can be used to assign compositions to all material streams. Since the total mass of each input and output stream is known, the theoretical mass of each element entering and exiting the furnace can be calculated. This is illustrated in Table 3-1, where \( A_i \) (lit) refers to the mass of element “1” present in stream “A” (based on literature composition).

<table>
<thead>
<tr>
<th>Stream</th>
<th>Mass per element (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>( A_1 ) (lit)</td>
</tr>
<tr>
<td>B</td>
<td>( B_1 ) (lit)</td>
</tr>
<tr>
<td>C</td>
<td>( C_1 ) (lit)</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>n</td>
<td>( n_1 ) (lit)</td>
</tr>
</tbody>
</table>
3.3.3 Update the assumed compositions with measured plant data

After the literature compositions were used to assume the mass of each element, actual plant data can be used to replace the data from literature. For the purpose of this example, note that composition data for streams A and C was available. This is illustrated in Table 3-2, where “A₁ (lit)” was replaced by “A₁ (actual)”.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Mass per element (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A₁ (actual) A₂ (actual) A₃ (actual) ... Aₓ (actual)</td>
</tr>
<tr>
<td>B</td>
<td>B₁ (lit) B₂ (lit) B₃ (lit) ... Bₓ (lit)</td>
</tr>
<tr>
<td>C</td>
<td>C₁ (actual) C₂ (actual) C₃ (actual) ... Cₓ (actual)</td>
</tr>
</tbody>
</table>
| ...    | ... ... ... ... ... ... ... ... ... ...
| n      | n₁ (lit) n₂ (lit) n₃ (lit) ... nₓ (lit) |

3.3.4 Visualising results

Once all streams are updated with actual plant data (where available), the results of the mass balance can be visualised in various different ways. An example of a desired plot is the total mass in vs. total mass out (based on Equation 3-2). This plot is shown in Figure 3-3:

![Visualising results](image)

Figure 3-3: Visualising results

A final mass balance error can also be calculated by using the following equation:

\[
\text{Mass balance error (\%) } = \frac{\sum(M_{\text{in}}) - \sum(M_{\text{out}})}{\sum(M_{\text{in}})} 
\]

Equation 3-3

For the purpose of this study, an error margin of 3% has been chosen as an acceptable error.

3.4 Final methodology

The three steps (from section 3.1, 3.2 and 3.3) can be combined to present the final methodology to be followed for developing a material balance over a FeCr furnace (presented in Figure 3-4).
4. CASE STUDY: RESULTS AND DISCUSSION

The final methodology is applied to an industrial case study and is used to highlight the specific outcomes of the method.

4.1 Collect information, layouts, and data

Furnace X is evaluated in terms of the methodology. A layout of the furnace, the relevant points of measure as well as the corresponding mass and composition data over a three-year evaluation period has been collected. This is shown in Figure 4-1.

Chrome ore, reductant (anthracite, char, and coke), and fluxes (dolomite, limestone, and quartz) are sampled on delivery (dataset “a”). Chromite ore is pelletised (PSP), and sampled again before batching (dataset “b”).
The composition of the FeCr metal and slag is also determined when exiting the furnace (dataset “c”). The mass of all raw materials is determined in weigh bins right before batching, whereas the FeCr metal and slag mass are measured at weigh bridges (dataset “d”).

These four datasets have been collected so as to be evaluated throughout the next step (4.2). Note that the slag mass meter is indicated in orange. This is due to the slag mass only being logged per month, when the rest of the data is in daily resolution. Thus, all data will be converted to monthly resolution when processing and calculations commence.

The time delay that may occur between mass and composition measurements is uncertain. All compositions will therefore be averaged to a constant annual value, in order to compensate for any possible storage capacities.

4.2 Evaluate data quality

The raw datasets as received in 4.1 (datasets “a”, “b”, “c”, and “d”) were evaluated based on the method discussed in Section 2.3. Figure 4-2 illustrates one of the datasets before and after the dataset has been cleaned.

![Figure 4-2: Data quality evaluation](image)

Any abnormal measurements within the data have been identified, investigated, and removed if necessary. Annual shutdowns were detected (where furnace was shut down for a month or two), however data was not removed since this is not an abnormal operational occurrence. Consequently, after applying the method of data quality evaluation, all datasets are of high quality and can be used in the final step to construct a mass balance.

4.3 Constructing a mass balance

4.3.1 Calculate total mass of unmeasured streams

From Section 4.1 it was noted that the only unknown mass is that of the off-gas stream. By using Equation 3-1, the mass of the total off-gas stream can be calculated:

\[
M_{\text{ore}} + M_{\text{reductant}} + M_{\text{flux}} = M_{\text{FeCr}} + M_{\text{slag}} + M_{\text{off-gas}}
\]

\[
M_{\text{off-gas}} = M_{\text{ore}} + M_{\text{anth}} + M_{\text{char}} + M_{\text{coke}} + M_{\text{dolomite}} + M_{\text{limestone}} + M_{\text{quartz}} - M_{\text{FeCr}} - M_{\text{slag}}
\]
Since all mass streams are now known, the next phase of constructing a mass balance can be investigated.

4.3.2 Assume the composition of all streams

Table 2-1 is used to assign compositions to all material streams. Since the total mass of each input and output stream is known, the theoretical mass of each element entering and exiting the furnace is calculated. This is illustrated in Table 4-2, where the pink blocks represent mass per element (calculated by using literature compositions).

### Table 4-1: Calculating the total mass of unmeasured (off-gas) streams

<table>
<thead>
<tr>
<th>Date</th>
<th>Consumption</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>REDUCTANT</td>
<td>FLUX</td>
</tr>
<tr>
<td></td>
<td>Anth.</td>
<td>Char</td>
</tr>
<tr>
<td>Jan-15</td>
<td>x xxx</td>
<td>0</td>
</tr>
<tr>
<td>Feb-15</td>
<td>x xxx</td>
<td>0</td>
</tr>
<tr>
<td>Mar-15</td>
<td>x xxx</td>
<td>0</td>
</tr>
<tr>
<td>Apr-15</td>
<td>x xxx</td>
<td>0</td>
</tr>
<tr>
<td>May-15</td>
<td>x xxx</td>
<td>0</td>
</tr>
<tr>
<td>Jun-15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jul-15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Aug-15</td>
<td>xxx</td>
<td>0</td>
</tr>
<tr>
<td>Sep-15</td>
<td>x xxx</td>
<td>xxx</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec-17</td>
<td>x xxx</td>
<td>xxx</td>
</tr>
</tbody>
</table>

### Table 4-2: Mass per element based on literature compositions

4.3.3 Update the assumed compositions with measured plant data

Actual plant data can be used to replace the data used from literature. As indicated in Figure 4-1, all streams’ compositions are available, except for the off-gas. This is illustrated in Table 4-3, where the pink blocks represent mass per element calculated by using literature compositions, and the green blocks represent mass per element calculated by using actual measured plant data.
4.3.4 Visualising results

The data of the mass balance is visualised in various ways in order to see the results of certain key parameter indicators. The following visualisations will be provided:

- Cr from ore vs. Cr in FeCr product
- Fe from ore vs. Fe in FeCr product
- Total C in vs. C in product
- Total mass in vs. total mass out

Each of these visualisations will be provided and discussed briefly.

**Cr from ore vs. Cr in FeCr product:**

The amount of Cr in the ore, trended together with the amount of Cr present in the final metal product, ultimately gives an idea of the recovery of Cr from the furnace. This trend is shown in Figure 4-3.

![Cr (ore) vs. Cr (FeCr product)](image)

**Figure 4-3: Cr from ore vs. Cr in FeCr product**

These two lines must be as close together as possible, which would indicate that most of the Cr fed to the furnace is recovered in the final FeCr metal product. In this case, the relationship between the two streams seems to be typical, with the exception of April 2016. Here, the amount of Cr in the product exceeds the amount of Cr fed by the ore, which is not possible. Further data investigation can be done when such an incident occurs.

The variance between the two lines is calculated to be 18%, which means that there was a 100% - 18% = 82% recovery of chrome. This correlates well with the value found in literature (as stated in section 2.2: between 80 and 85%).
Fe from ore vs. Fe in FeCr product:

The visualisation of Fe is similar to that of the Cr, discussed in the previous point. The Fe trend is shown in Figure 4-4.

![Figure 4-4: Fe from ore vs. Fe in FeCr product](image)

Once again, the relationship between the two streams seems to be typical, with the exception of April 2016, as discussed previously. The difference between the variables is calculated to be 12%.

Total C in vs. C in product:

The total amount of carbon entering the furnace, trended together with the amount of carbon in the metal product, ultimately shows how much carbon is captured in the solid phase. The difference between the two lines would typically represent the amount of carbon emitted as part of the off-gas. The trend is shown in Figure 4-5.

![Figure 4-5: Total C in vs. C in product](image)

It can be seen that the difference between the two lines is quite significant. The calculated difference is 86%, which means that 86% of the carbon used in FeCr production is emitted to the atmosphere (usually in the form of CO and CO₂). Further studies are in progress, focusing on off-gas emissions specifically [35].

Total mass in vs. total mass out:

The aim of this study is to perform a material balance on a typical ferrochrome furnace, which will be the final visualisation. The total mass of elements entering the furnace will be plotted against the total mass of elements exiting. This is shown in Figure 4-6.
Ideally, one would expect the two lines to follow the exact same trend, which would indicate a ‘good’ mass balance. This is almost the case, where a 1.25% discrepancy is found between the mass in and the mass out. This remains within the 3% error margin of an acceptable error, as chosen for this study.

Generally, the remaining results (not shown) also correlated well within the limits of typical mass ratios of input and output streams found in literature (as provided in section 2.2, p. 5).

5. CONCLUSION

This paper provided a brief overview of the furnace parameters measured in practice, before presenting an approach to perform the material balance. The available measurements of input and output streams were used together with compositions from literature. The analytical approach linked the known composition together with the known mass, to estimate the unknown streams.

The approach was applied to an industrial case study. The analysis managed to balance all elements (in and out) within an accuracy margin of 1.25%. Completing the mass balance up to this point can significantly decrease limitations on decision-making abilities.

6. BIBLIOGRAPHY


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1 Knowledge gained from site experience and interviews with site personnel
2 Knowledge gained from site experience and interviews with site personnel