Non-linear State Estimator for the On-line Control of a Sinter Plant

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This is a thermal control model that aims to increase sinter process stability and standardize control criteria using the position and temperature of the sintering point or BTP calculated by the model. The process computer sends to the instrumentation setpoints of return fines, strand speed and coke content. The model was successfully tested at the facilities of AM Asturias with contrasted improvements in productivity, coke consumption and quality stability.

KEY WORDS: sinter; burn-through point; mathematical model; simulation; industrial control; raw materials; ironmaking; filter.

1. Introduction

Sintering process is the most widespread method to agglomerate the iron ore in the steel industry. In Asturias ArcelorMittal works, as in most industrial plants, this is usually carried out in a Dwight-Lloyd (DL) machine (Fig. 1) where iron ore is sintered after a thermal treatment process.

During the sintering process, a mixing of different kinds of materials, previously pelletized, are discharged onto a moving strand and leveled to form a homogeneous bed. An ignition furnace starts combustion of the upper layers at the beginning of the bed. A large fan sucks air down through the bed to the wind boxes equipped with thermocouples that measure the temperature of the sucked gas. The sinter product is formed along the strand through the physical and chemical processes occurring within the bed. Combustion of coke takes place in a flame front which spreads throughout the bed. This flame front should reach the grate of the machine at a certain distance before ending the strand, since the cooling stage should begin in the last part of the strand. It has been demonstrated that the optimal distance is that approximately corresponding to the last but one wind box, since sinter product needs to cool before discharging; furthermore, it is important to improve the strand utilization by increasing the proportion of air used for the sintering process and not for cooling the final product.

Finally, the sinter gets cold in a rotary cooler. After being discharged, the material is classified in a screen and products of acceptable size are carried to the blast furnace by means of several conveyor belts. On the contrary, too small pieces of product are returned in order to be reprocessed. This kind of product is usually called return fines (RF). Another part of the product with middle size is used as hearth sinter and it provides support for the sinter bed.

At the moment, two sintering plants are working in ArcelorMittal plant, in Asturias. On one hand, plant A is 65.1 meters long and 4 meters wide. This plant is made up of 21 wind boxes. On the other hand, plant B is 87 meters long and 3.2 meters wide. In this case, there are 23 wind boxes along the machine. Strand speed is about 2.8 and 3.2 m/s, respectively, and gas flow passing through the sinter bed is higher than 750 000 Nm3/h in both plants. Sinter production in both plants is about 5 500 000 tons of sinter product per year. Regarding the productivity, it reaches a value around 32 t/m2/24 hours as an annual average in both plants.

2. Control Problems

Operation of a sinter plant is quite a complex task for the operators. They have a lot of responsibilities, not only in the mechanical part but also in the process itself. Here, we can sum up, the most important worries of the operator:

1. Failures in the sinter feeding, from the preparation site to the charging hoppers
2. Irregular composition of materials in the charge
3. Failures in the supply of gas to the ignition furnace

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In this paper, a simple control system is proposed. The operator is so constantly forced to supervise both the machine and the process. He has to deal in some cases with too many variables. Here is a list: machine speed, coke recipe, returns fine recipe, limestone recipe, humidity, air flow to ignition furnace, gas flow to ignition furnace, feeding roller speed, cooler speed, layer height, sinter bottom layer.

Environment regulations are every time more and more restricting. Exhaust gas temperature to the chimney is controlled by the operator to keep it between certain limits. Higher than 140°C to avoid dioxin formation and to reduce emissions after the electric precipitator, and lower than 160°C for safety reasons. The dust is considered to act as nucleation sites for mist condensation and sulfuric formation.

There exist not a lot of works in the literature about BTP determination. Burn-through point (BTP) is defined as the point where the temperature of the waste gas reaches its highest value. It occurs when the flame front reaches the bottom of the sinter bed. It is traditionally admitted that keeping stable this point conveys stabilization of the process and improvement of both quality and productivity.

The other important reaction considered is the evaporation of water. In this case, it has been supposed that coke combustion, water evaporation, carbonates breakdown and hematite reduction in two steps.

\[
\begin{align*}
C + O_2 & \rightarrow CO_2 \\
H_2O & \rightarrow H_2O_G \\
CaCO_3 & \rightarrow CaO + CO_2 \\
Fe_3O_4 & \rightarrow Fe_2O_3 + O_2 \\
FeO & \rightarrow 3FeO + 1/2O_2
\end{align*}
\]

It is extremely complicated to know the reaction rates of every process so attempts were made to have a thorough knowledge of these questions. It was necessary to take into account some considerations which are described below.

- Coke combustion has been supposed as a total combustion happening at approximately between 800 and 1300 centigrade degrees. In excess of oxygen the combustion of coke to CO₂ could be considered proportional to the temperature and concentration. This ratio is adjusted assuming complete combustion at the end of the strand and initiated at temperatures above 800°C. It is also important to point out that this reaction only occurs when all the water contained in the specific layer has previously been evaporated.

- The other important reaction considered is the evaporation of water. In this case, it has been supposed that...
this evaporation takes place when temperature is about 100 centigrade degrees. Furthermore, it has been considered two different water evaporation rates, one below the ignition hood and one after it in order to take into account the different input gas temperatures. Always considering plant data, we assume all the water should be vaporized before BTP. Because of the special condition of temperature and pressure under the hood this ration has been increased from experimental data in this zone.

- Carbonates breakdown usually takes place in the preheating zone of the sinter bed, that is, before the flame front, and it has been considered occurring between 800 and 1100°C. The speed was adjusted for a complete decomposition inside this range. The reaction rate was estimated as it is explained below. Considering all of these aspects, reaction rates have been calculated according to the concentrations of each material. Initial values were estimated taken into account strand speed and operator knowledge:

\[ r(i) = c(i) \times f \]  \hspace{1cm} (1)

Where: \( r(i) \) is the reaction rate, \( c(i) \) is the concentration, \( f \) is a correction factor.

Proportioning of coke, mineral, lime, water and returning fines were considered to calculate different concentrations at each moment.

However, reaction rates not only depend on the raw materials and its concentrations, but also on the air blowing and the temperature of the sinter bed or, in other words, the temperature of the main gas collector. Thus, reaction rates were in some way modified according to these parameters based on empirical evaluation. For instance, the coke combustion rate should be that all the coke is transformed at the end of the process. A simple proportional connection between reaction rates and gas flow was entered in the code.

On the other hand, heat balances for both gas and solid phases have been established. In this case, only coke combustion and water evaporation have been considered, since it has been demonstrated that these two chemical reactions constitute more than 80 per cent of the total energy involved in the whole of sintering process. Input and output heat flows, exchange heat between solid and gas phases, chemical reaction heat and conduction between consecutive layers have been taken into account to calculate the temperature of solid and gas phases at any point of the sinter bed.

Heat balances have been applied to each one of the phases described above in every working section:

Gas heat balance

\[ M_g \cdot c_{es} \cdot \frac{dT_g}{dt} = -d \frac{d}{dy} \left( q_g \cdot v_g \cdot c_{es} \cdot T_g \right) + f \cdot \sum H_i \cdot r_i + h_c \cdot (T_s - T_g) \]  \hspace{1cm} (2)

Solid heat balance

\[ M_s \cdot c_{es} \cdot \frac{dT_s}{dt} = (0.4) \sum H_i \cdot r_i - h_c \cdot (T_s - T_g) + k \frac{dT_s}{dc^2} \]  \hspace{1cm} (3)

Where: \( M_g \) is the gas mass, \( M_s \) is the solid mass, \( c_e \) is the specific heat, \( f \) is an experimental factor, \( H_i \) is the reaction enthalpy, \( T_g \) is the gas temperature, \( T_s \) is the solid temperature, \( h_c \) is the heat transfer coefficient, \( k \) is the conduction coefficient, \( t \) is the time, and \( r_i \) is the reaction rate.

Gas mass is calculated from the mass conservation equation for every specie in solid and gas phases:

\[ \frac{dq_g}{dt} = \sum r_i \]  \hspace{1cm} (4)

\[ \frac{dq_w}{dt} = -\frac{d}{dy} \left( q_w v_g \right) + \sum r_i \]  \hspace{1cm} (5)

Gas mass used in heat balance is calculated as result of a mass balance follows depending on atomic mass and mass flow of each compound:

\[ M_g = \sum m_i \cdot q_i \]  \hspace{1cm} (6)

Where: \( m_i \) is the atomic mass; \( q_i \) is mass flow; \( v_g \) is the gas speed and \( r_i \) is the reaction rates.

### 3.2. The Filter

Differential Eqs. (2) and (3) above made for heat balances can be written in simplified form by the following model:

\[ \frac{dT}{dt} = f(T, u, t) \]  \hspace{1cm} (7)

This equation is a dynamic model, but according to the “Modern control theory” for application to real processes, normally called stochastic processes, two basic conditions must be met. The model must be “filtered” and must be “observable”. “Filtered” makes reference to the treatment of real data from the process, poor and good data, by the model (Fig. 3). While “observable” makes reference to the convergence of the mathematical model. Convergence to solution must be obtained regardless of initial conditions. The literature speaks in these cases as asymptotic state estimator. Kalman filters are a popular example for linear systems.

In our case the correction or filtering is achieved by comparing wind boxes temperatures, measured and calculated. The differences are introduced into the model by their equivalent in false air; which is air not involved in the reaction and cooling down leaving gas temperatures at the bottom of the bed. A simple thermal balance will conclude:

\[ M_g \cdot T_g + M_f \cdot 25 = (M_g + M_f) \cdot T_m \]  \hspace{1cm} (8)

Where: \( M_f \) is the false air; and \( T_m \) the measured wind boxes temperatures.

The new gas flow Mg calculated from (8) is entered into the heat balance (2) in order to recalculate the gas temperatures.

Finally the filter equations take the following non-linear shape:

\[ \frac{dT}{dt} = f(T, u, (T_m - T_c), t) \]  \hspace{1cm} (9)

\[ T_c = q(T, t) \]

Where: \( T \) are the calculated temperatures, gas and solid, inside the bed; \( T_m \) the measured wind boxes temperatures; \( T_c \) the calculated wind boxes temperatures; \( u \) are other input variables; and \( t \) the time.

Concentrations and temperatures are calculated on-line at any point of the sinter bed. Furthermore, gas temperature of
each wind box is also estimated and used for calculating the BTP position and temperature.

The proposed model also considers changes in activity of coke, mainly affected by its grain size.

Increased coke activity brings backward sintering point and an increase of wind boxes temperatures (Fig. 4). Useful air will rise to match the actual values.

4. Model Validation

Calculated wind boxes profile is shown to the operator. It has been observed that differences between real and estimated profiles are due to errors in thermocouples measurements. It is well known that thermocouples, at those working temperatures, are commonly damaged and their values are not totally reliable. In fact, they are often necessary to replace.

Thus, it can be observed the wrong thermocouple measurement in a certain moment and to compare this one with the temperature profile obtained with our sintering model, it is very important to point out that the model developed at this paper has been validated in two real plants according to the evolution of sintering process during twelve months. This point is extremely important, since the same model has demonstrated a good response for both industrial plants. The results obtained by the modeling show a good correlation between estimated variables and real measurements.

Some of these results are shown in a typical temperature/time diagram, showed in the Fig. 5. In this picture, estimated BTP temperature and real temperature of waste gas in wind boxes 19 are shown. The strong variation of the temperatures should be explained as consequence of normal process variations in composition, humidity, size, density and distribution of the material in the bed at the charge.

Size, density and distribution are not explicitly considered in the modelization. The influence of these parameters is taken into account in an indirect way by the model through changes in boxes temperatures.

It is observed a higher value of estimated temperature than the real one which is due to the air leakages as it was explained above. Thus, not-utilized air cools the temperature of the gas passing through wind boxes. Quantities of this air are so significant to determine the real gas temperature. In fact, it has been found in the literature that air leaks can reach above the half of the total induced air.

Therefore, air leakages in every wind boxes along the sintering machine are also estimated by the mathematical model and they are used to correct the reaction rates. In this case, air leaks have even reached about the 60 per cent of the total air getting into the machine.

Main collector temperature can be calculated from the wind boxes temperatures estimated by the model. The result shows a good correlation with the measurement. See Fig. 6.

There is also a good correlation between the calculated

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Fig. 3. Filter flow chart.

Fig. 4. Effect of coke activity on the BTP position.

Fig. 5. BTP temperature versus windbox-19 temperature r = 0.66.

Fig. 6. Dust collector temperature measured and calculated r = 0.8.
BTP position and the temperature at the crusher at the end of the sinter bed (Fig. 7). As it was expected when the sintering process moves to the end, the temperature at that point increases. This is an excellent indicator of the BTP position since there exists no measures of real BTP position.

5. Heat Balance

Consumed and generated heat during the sintering process is estimated by means of heat balances according to the results previously mentioned. Heat is mainly released because of the combustion of coke and, to a lesser extent, of the ignition hood. A typical heat balance in our sintering plants is shown in Table 1.

Studying the heat that is necessary to carry out the evaporation of water and the breakdown of carbonates, it can be estimated the quantity of heat that is consumed because of the two most important endothermic reactions. But air drawing through the bed also gets heat out of the machine in a quantity of great importance. And not only utilized air, but also not-utilized air takes a minor part of heat out of the sintering machine. Besides this, the sinter bed reaches the end of the machine with quite high temperature and therefore an important quantity of heat is lost in this sense. Finally, it is important to take into account the quantity of heat that is liberated through the gas collector. This term completes the global heat balance of the sintering process. The importance of every heat term is also evaluated on-line by the model.

Table 1. A typical global heat balance.

<table>
<thead>
<tr>
<th></th>
<th>ENDOT. (Mcal/h)</th>
<th>EXOT. (Mcal/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke combustion</td>
<td>–</td>
<td>95 301</td>
</tr>
<tr>
<td>Ignition hood</td>
<td>–</td>
<td>6 299</td>
</tr>
<tr>
<td>Water evaporation</td>
<td>9 855</td>
<td>–</td>
</tr>
<tr>
<td>Breakdown carbonates</td>
<td>7 722</td>
<td>–</td>
</tr>
<tr>
<td>Utilized air</td>
<td>19 914</td>
<td>–</td>
</tr>
<tr>
<td>Not-utilized air</td>
<td>6 909</td>
<td>–</td>
</tr>
<tr>
<td>Sinter bed</td>
<td>46 634</td>
<td>–</td>
</tr>
<tr>
<td>Leaks</td>
<td>10 566</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>101 600</td>
<td>101 600</td>
</tr>
</tbody>
</table>

Figure 8 shows an approximate heat balance for the process during the normal plant running in the form of a Sankey diagram.

6. The Control

Under the separation principle of modern control theory this process can be controlled using the estimated temperatures calculated by our model instead of using the actual measures taken by the instrumentation. The initial idea was to use these temperatures to calculate the sintering point and then use it to control the process. The BTP position and temperature would determine the strand speed and the coke consumption respectively. In early tests it was found the additional importance of keeping within a range the temperature of the collector, strongly affected by the position of the maximum. When the maximum is close to the burner the collector temperature will be higher and vice versa. Therefore we decided to introduce the collector temperature in the formula of speed control.

Using the position of the BTP and collector temperature we calculate the variation of the speed relative to the reference speed, normalized to a blow of $Q_{ref}$, allowing giving the following expression:

$$V = V_{ref} \cdot \frac{Q_v}{Q_{ref}} + k_1 \cdot (T_C - T_{ref}) - k_2 \cdot (x_{BTP} - x_{ref}) \ldots \ldots (10)$$

Where: $V_{ref}$ reference speed normalized; $Q_v$ the wind flow...
m3/h; \( T_c \) collector temperature; \( T_{r f} \) collector reference temperatures; \( x_{BTP} \) the sintering maximum position; \( x_{r f} \) the reference position.

On the other hand the consumption of coke is known regarding the FeO produced, see Fig. 9. The correlation is quite high, \( r = 0.41 \).

And as expected there is a strong correlation between the BTP temperature and the normalized coke (for 30% of return fines), \( r = 0.61 \). BTP temperature moves around 1050°C (Fig. 10).

It suggests for the control the following relationship:

\[
C = C_{r f} \cdot \frac{100 - 0.6 \cdot RF}{70} - k \cdot (T_{BTP} - T_{r f}) \quad \text{........ (11)}
\]

Where: \( C_{r f} \) is the normalized coke to 30% return fines; \( RF \) return fines; \( T_{BTP} \) is the BTP temperature; and \( T_{r f} \) the reference temperature.

The problem arises when analyzing long periods of time. The chart below Fig. 11 shows how the BTP temperature for a period of one month had a downward trend opposite to that of ferrous.

It seems clear that the reference temperature is not fixed and depends on factors not included in the model depending on the composition of the piles and the driving conditions. Although it was firstly considered a constant BTP reference temperature depending only on composition of piles, it was later necessary to include a correction factor according to FeO analysis.

Therefore it was decided to adjust the reference temperature, taking into account the ferrous, just as the plant operator does to adjust coke. The more ferrous the more reference temperature and therefore less coke:

\[
\Delta T_{r f} = -A_{FeO} \cdot 40 \quad \text{........ (12)}
\]

The factor 40 was obtained statistically from the available data.

The return fines were under a simple control as a function of the hopper level:

\[
RF = RF_{r f} + k \cdot (Level - Level_{r f}) \quad \text{........ (13)}
\]

The proposed controls are not innovative; we could say that it is the same. The operator of the sinter has always used the windboxes temperatures to get an idea of the position of the sintering point. The model works in the same way, fixing speed and coke using the position of the BTP calculated, that is, a better filtered signal from box temperatures. This approach is intended to make the control more resistant to noise and disturbance in the measures of windboxes temperatures. On the other hand we must not forget that our model is a thermal model that attempts to stabilize the operation from this point of view mainly. It is assumed that variations in composition, grain size and permeability, not explicitly included in the modelization, will affect heat in the process and will be corrected by the model being filtered by the real signals.

7. Put in Operation

Model has been running in both plants since December 2008. Testing and reengineering of formulation were constantly done. But it wasn’t until June 2012 that we started the real online tests on sinter plant A. The results have been really satisfactory. Independently of the improvements in operational parameters, operators and staff find the model a good way for action standardization. Foreman’s setpoints can be more easily achieved now and the operator has more time for monitoring the rest of the process.

Three different periods of time between programmed stoppages were considered (Fig. 12). Wide variety in productivity through these periods is a typical behaviour in sintering process due to filtrations and leaks which appear in the facility with time. During these periods, process and installation conditions were similar so it was possible to compare results in a manual and in a model way. It is important to point out that data were filtered in an exhaustive way.

There has been an improvement in the productivity of 4–5% (from 34.9 to 36.5 t/m2/d, see Table 2). Regarding the coke, it is reduced from 5.5 to 5.2%, and return fines from 45 to 37%. It has been appreciated also the improvement of...
the deviation values of FeO, critical parameter for the performance of the blast furnace, up to 20% less.

Results obtained are better than expected, and the standardization is a great advantage, but how does the model get it? The key must be found in the improvement of stabilization of all the controls, specially the BTP position. Better return fines control conveys better adjustment in coke addition and in BTP position. Another point not clearly identify previously was the importance of keeping the BTP temperature as constant as possible and at the correct value. This latest point is conditioned by the ferrous percentage in the final product.

8. Conclusions

In this paper, a sinter process mathematical model has been developed for the purpose to control the burn-through point in sintering plants. This model has been developed in accordance with estimation and control theories of stochastic processes. This is a robust model and it has been proved that it does not change much with errors of process signals. The most important modelization factor has turned out to be the quantity of not-utilized air, that is, the air that has not a direct utility for the sintering process.

Temperatures profile along the sinter bed has been established from mass and heat balances. Consequently, burn-through point position and temperature have been identified from different initial conditions. Besides this, BTP position and temperature have been used in the control algorithm and it has been possible to use strand speed and consumption of coke as control variables, respectively.

According to these results, it can be said that the model is useful for the sintering process optimization, since not only can reduce the consumption of fuel, but also it is able to increase sinter productivity and quality.

In view of the good results above presented for sinter plant A, we have already changed the same automation screens on sinter B. It is production department intention to start with the online trials also in this facility this year.

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REFERENCES


<table>
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<tr>
<th>Periods 2012</th>
<th>Productivity t/m²/d</th>
<th>Coke %</th>
<th>Return Fines %</th>
<th>σFeO</th>
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<tr>
<td>20/4–8/6 Manual</td>
<td>34.91</td>
<td>5.51</td>
<td>45</td>
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<tr>
<td>16/6–24/7 Model</td>
<td>36.81</td>
<td>5</td>
<td>34.56</td>
<td>0.55</td>
</tr>
<tr>
<td>28/7–5/9 Model</td>
<td>36.14</td>
<td>5.35</td>
<td>39.03</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Fig. 12. Sinter plant productivity.