A VIRTUAL LD-STEEL-CONVERTER

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Abstract. The software for the static control of the LD steelmaking process has been presented, based on a detailed physico-chemical model. The software is able to calculate the optimum charge composition and the amount of oxygen to be used to achieve target temperature and C-content of steel, during blow. The software can be used also in training of steelmakers, as it can simulate the LD-process. The influence of different parameters on the steel temperature has been obtained in this paper. Our data are confirmed by empirical thumb rules established empirically in the plant. However, when several parameters are changed at the same time, the thumb rules fail, as the process is not linear. In this case the software should be used to achieve optimum process parameters.

Introduction

Oxygen steelmaking is a complex technology characterized by short cycle time [1-4]. The time allowed to make decisions is so short that good control of processes can be guaranteed only with the aid of a computer. In the present paper a software tool is described, providing the steelmaker by proposals on the optimal composition of the given charge and on the amount of oxygen used for the given charge, depending on the present status of the converter, on the composition and temperature of ingredients and on the values of the target parameters (temperature and carbon content of steel).

1. Possibilities to build models of industrial scale

A given industrial process can be modelled in two different ways. The easiest way to build a model is to find an empirical correlation between the input and output parameters of the process, without any insight into the real physical phenomena taking place during the process. Neural network systems is an ideal tool for building such empirical models. The another, more complicated (but also more promising) way of model building is when all physico-chemical processes taking place in the given process are taken into account and described mathematically in a complex software. In complex technologies such as oxygen steelmaking, a purely theoretical model is very hard to create as (non-equilibrium) chemical thermodynamics and kinetics should be coupled with complicated mass and heat transfer phenomena in a 4-phase system (liquid metal, molten slag, gas, solid wall and solid, partially un-dissolved phases). Therefore, in the present work a semi-empirical way to describe oxygen steelmaking was chosen as a compromise between purely theoretical and purely empirical ways of modelling.

Our model should satisfy the following criteria:

i. describe all the significant sub-phenomena taking place during the process,
ii. to be theoretically correct in each step of description,
iii. to be suitable for making a computer algorithm to describe the whole process.

The following two stages of model-building can be distinguished:
i. development of the general model structure of the given process (oxygen steelmaking, in general),

ii. model-adaptation, i.e. determination of the values of those semi-empirical parameters, what make the general model applicable to the given device and industrial practice (for the particular oxygen steelmaking process).

In modelling metallurgical technologies usually the rules of conservation of mass, energy (heat) and impulse are used to build the models. Therefore, the steps to create complex technological models can be described as follows:

i. division of the apparatus (in space) and the process (in time) into the quasi-independent sub-spaces and sub-processes,

ii. identification of input- and output parameters of the sub-spaces and sub-processes,

iii. definition of the conservation (balance-) equation for all sub-spaces and sub-processes,

iv. building the complex model by summation of sub-spaces and sub-processes, by identifying the necessary semi-empirical parameters of the given model,

v. determination of the above identified semi-empirical parameters for the given particular process, based on a data-bank obtained from the real measurements on the given apparatus.

2. The physico-chemical basis of the LD-steel-converter

Oxygen steelmaking by LD-technology is a very complex technological process, including the charge of liquid pig iron + solid steel scrap + other solid materials (lime, etc) into the converter, followed by the blow of oxygen into the semi-liquid bath, and later tapping the liquid steel and molten slag, once the technological goal, described usually by two target parameters has been achieved. The technological target parameters are usually the final temperature and the final carbon content of the steel after the process. The process and its control schemes is shown schematically in Figure 1.

![Figure 1. The process of oxygen steelmaking, and its control schemes (schematic)](image-url)
The goal was to create a semi-empirical model and the software (i.e. the virtual LD-converter), being able to provide the steelmaker by the following information:

i. based on the state of the converter, availability of materials and their properties, and also the target parameters, to calculate an optimum composition of the next charge, i.e. the amounts of liquid pig iron, solid steel scrap and additional materials (such as lime), and also oxygen gas (see solid lines in Fig.1),

ii. based on the actual amounts charged into the converter (which can be different from the above suggested optimum values), to calculate the optimum blowing time and amount of oxygen to be used, for both the target-temperature (usually about 1670 °C) and target-carbon content of steel (usually 0.045 w%); these two calculations provide the same result only, if the actually charged amounts are the same as the optimum charge composition suggested above (see dashed lines in Fig. 1).

Based on the above, the static theoretical LD-model is an inverse problem, shown schematically in Fig.2.

Fig. 2. The scheme of the static theoretical LD-converter model

3. Summary of the physico-chemical model

The model basically consists of two parts: the material and the heat balance. The material balance is basically done for the final carbon-content of the steel, while the heat balance is basically done for the final temperature of the steel. Although the aim of the material and heat balances are limited, the full material and heat balance of the process should be designed.

During the process about 80 parameters are measured for each charge. From the point of view of the model development and the software to be written for the static control of the process, the data should be grouped according the moment of their availability.

Before starting the process the following data are available:

i. the composition (C, Si, Mn, P, S) and temperature of the liquid pig iron,

ii. the quantity of the pig iron and the steel scrap is given by the steelmaker (or by the software to be developed),

iii. the composition of lime (CaO, MgO, CO₂),

iv. the outside temperature, characterising the temperature of scrap and lime,

During the process the exact quantity of the lime and CaF₂ added is measured. These quantities should be defined by the steelmaker or by the software, and are usually calculated based on the amounts and composition of pig iron and scrap. After the process the following additional data are obtained:
i. the composition of the steel produced (C, Mn, Si, P, S),
ii. the composition of the slag (SiO$_2$, CaO, FeO, MgO, MnO, Al$_2$O$_3$, P$_2$O$_5$, S),
iii. the final temperature of the steel,
iv. the amount of oxygen used for the process (in m$^3$ related to 20 °C and 1 bar).

The later data have been known during the model development for 4,000 charges, but should be calculated by the software during the real static control of the process. The quality of the software is actually characterised by the deviation between the previously calculated and the later measured data. At the stage of model development all the above data were taken from the data-bank of 4,000 industrial charges.

From the ‘full’ characterisation of the 4,000 produced charges at Dunaferr Works listed above, the materials balance for non-volatile components can be composed (Si, Mn, Ca, Mg, P, Al)$^1$. To our great surprise, significant and reproducible dis-balances were found for Si, Mn, Ca, Mg and Al [5]. Moreover, correlations have been established between the dis-balances of Si, Mn and Ca for different charges. These observations could be explained only, if one supposes that some additional materials appear in the charge, in addition to those, realised by the steelmaker today. This additional material is much probably non-metallic, having higher SiO$_2$, Al$_2$O$_3$ and MgO-content, and lower CaO and MnO-content compared to the steel slag. There are basically two possible sources of such an additional material [5]:

i. ‘dirt’, charged into the converter together with the steel scrap (the scrap is far from being ideally clean – it is obvious even from its visual observation) – its amount is weighed and reported together with the real (and unknown) weight of the scrap,
ii. the liquid pig iron slag, carried into the converter on the top of the liquid pig iron – its amount is weighed and reported together with the real (and unknown) amount of liquid pig iron.

In addition to the above discussed two un-realised sources for the materials balance, there is always some un-dis-charge amount of steel slag, remaining in the converter from the previous charge, and dissolving in the new slag. Although its composition is known from the analysis of the previous charge, its amount is not known either. From the detailed analyses of the dis-balances of Si, Al, Mg, Ca and Mn the average amounts of the three new phases have been estimated as described below. Finally, the material balance during the model development was calculated as:

The amounts of oxidised components $m_{i,ox}$, kg (i = C, Si, Mn, P, Al):

$$m_{i,ox} = 10 \cdot \left[ (m_{pin} - m_{pin,slag}) \cdot C_i^{pin} + (m_{scrap} - m_{scrap,dirt}) \cdot C_i^{scrap} - m_{steel} \cdot C_i^{steel} \right]$$  \hspace{1cm} (1)

where $m_{pin}$, $m_{scrap}$ is the mass of liquid pig iron and steel scrap (t), as measured, i.e. without taking into account the amount of the pig iron slag $m_{pin,slag}$ (t) and the scrap dirt $m_{scrap,dirt}$ (t),

$C_i^j$ – the weight% of component i in phase j,

$m_{steel}$ (t) is the final amount of steel, calculated as:

$$m_{steel} = \frac{(m_{pin} - m_{pin,slag}) + (m_{scrap} - m_{scrap,dirt}) - 0.95 - 0.001 \cdot \sum_{i=C, Si, Mn, P, Al} m_{i,ox}}{1 - 0.01 \cdot L_O \cdot C_i^{slag}_{FeO}}$$  \hspace{1cm} (2)

$^1$ the Fe-balance is used to estimate the amount of steel – see below
where \( L_O = \frac{C_{steel}}{C_{FeO}^{slag}} \) – the distribution coefficient of oxygen between the steel and the slag,
\( C_{FeO}^{slag} \) is the total weight% of FeO and Fe\(_2\)O\(_3\), reported usually together in the slag chemical analysis,
0.95 t – is the amount of Fe lost during the process with the gas stream.

The amount of slag \( m_{slag} \) (t) can be calculated as:

\[
m_{slag} = \frac{m_{pironslag} + m_{scrapdirt} + m_{prevslag} + m_{nonmet} + 0.001 \cdot \sum_{j \in \{Si, Mn, Al, P\}} k_i \cdot m_i^{ox}}{1 - 0.01 \cdot C_{FeO}^{slag}} \quad (3)
\]

\( m_{prevslag} \) (t) – the amount of remained slag from the previous charge,
\( m_{nonmet} \) – the total mass of all non-metallic additions (minus their CO\(_2\) and H\(_2\)O content) charged into the converter, such as lime, etc., including 4 kg per charge of the lining of the converter,
\( k_i \) – the ratio of molecular mass of the oxide of component \( i \) to the atomic mass of component \( i \).

If the values \( m_i^{ox} \) for \( i = C, Si, Mn, P, Al \) and \( m_{steel} \) and \( m_{scrap} \) are calculated from Eq-s (1-3), the material balance for the non-volatile components (Si, Mn, Ca, Mg, Al) can be written as:

\[
k_i \cdot m_i^{ox} + 10 \cdot \sum_j m_j \cdot C_{i,ox}^j = 10 \cdot m_{slag} \cdot C_{i,ox}^{slag} \quad (4)
\]

where the summation by \( j \) is performed for ‘pironslag’, ‘scrapdirt’, ‘prevslag’ and ‘nonmet’,
\( C_{i,ox}^j \) – is the oxidised form of component \( i \) in the phase \( j \).

Equations (4) for all the 5 components Si, Mn, Ca, Mg, Al can not be all satisfied with only three free variables \( m_{pironslag}, m_{scrapdirt} \) and \( m_{prevslag} \). However, the combination of these three parameters can be optimised for each charge in a way that the minimal value of the total dis-balance of the 5 components Si, Mn, Ca, Mg and Al is obtained. As a result of performing this optimisation procedure for 4,000 charges, the average values were found [5]. During applying our software these values will be used as pre-set parameters. However, the steelmaker will have the option to change those parameters, as they have a serious influence on the reliability of the software (see the example below).

Now, the oxygen balance can be written, from the assumption that the average O\(_2\)-content of the oxygen gas is 98.5 %, and no O\(_2\) escapes to the gas phase from the gas blown into the converter. The oxygen balance is written in m\(^3\), corresponding to 20 °C and 1 bar:

\[
0.985 \cdot V_{OX} = \sum_{i = C, Si, Mn, P, Fe, Al} v_i \cdot m_i^{ox} + v_C \cdot \varepsilon \cdot m_C^{ox} + 280 + 7.616 \cdot C_O^{steel} \cdot m_{steel} \quad (5)
\]

where \( V_{OX} \) is the amount of oxygen gas blown into the converter,
\( v_i \) – are coefficients connecting the oxidised amounts (kg) and the m\(^3\): \( v_C = 1.0144 \),
\( v_{Si} = 0.8677, v_{Mn} = 0.2218, v_P = 0.9835, v_{Fe_2} = 0.2182, v_{Fe_3} = 0.3273, v_{Al} = 0.6021 \),
\( \varepsilon \) - the ratio of CO oxidised to CO\(_2\) in the gas stream,
280 m\(^3\) – corresponds to the 950 kg of iron lost,
the last term corresponds to the oxygen dissolved in steel.
From Eq.(5) the value of \( \varepsilon \) could be found for each charge. Its average value is \( 0.22 \pm 0.06 \) [5]. This value is in the reasonable interval, as it is indeed between the value 0.1 and 0.3 found experimentally in [6], and is close to the average value of 0.18 used in the previous material balance [7] designed for the LD process at the Dunaferr Works.

Based on the material balance, the heat balance was constructed [8]. It should be mentioned, that while the material balance is constructed on a purely thermodynamic basis, the heat balance should also involve kinetics, as the heat losses will be time-dependent.

From the point of view of the heat balance, the converter with a certain initial heat content + steel scrap, lime, and oxygen gas of the outside temperature + liquid pig iron of the measured initial temperature results into the final state of the steel, slag, gas and converter of a given final temperature/heat content. During the process the temperature increases due to exothermic oxidation reactions and due to the exothermic reactions of complex formation in the slag, while this heat is consumed for the heating of all the phases (including their melting) and for the heat loss to the environment. Thus, the heat balance can be written as:

\[
Q_{OX} + Q_{SLAG} + Q_{HEATING} + Q_{LOSS} = 0
\] (6)

The sign of the above terms are chosen according to thermodynamics: heat-evolving processes (\( Q_{OX} \) and \( Q_{SLAG} \)) are taken with a negative sign, while heat-consuming processes (\( Q_{HEATING}, Q_{LOSS} \)) are taken with a positive sign. At the given mass balance Eq.(6) is satisfied only at one given final temperature \( T_{Fin} \), if all the 4 terms are described as function of \( T_{Fin} \). During the model development the goal was to create such a model with reasonable semi-empirical parameters, which is able to reproduce the measured \( T_{Fin} \) values, while during the static control procedure the aim is to predict the value of \( T_{Fin} \) for a given material balance and other initial parameters (time intervals, initial temperatures).

Based on that, the algorithm of the static control was created, and a software developed on this basis was written [9].

Conclusions

Finally, our detailed material and heat balance allowed to reproduce with a reasonable accuracy the empirical (measured) data during the 4,000 industrial charges.

References