TOWARDS MODEL-BASED CLOSED-LOOP CONTROL OF THE BASIC OXYGEN STEELMAKING PROCESS

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Abstract: Model-based closed-loop control of the basic oxygen steelmaking process will give an opportunity to increase process operation performance. By using control algorithms that interact with thermodynamical and physical models capable of making real-time predictions of the effects of control actions, the time delays in order to wait for process response will be eliminated. Existing limitations like pre-set lance programs can be avoided. This paper outlines the concept of a recently started project aiming at model-based closed-loop control as well as present the initial work that has been made on the subject. *Copyright © 1998 IFAC*

Keywords: Model-based control, Closed-loop control, Physical models, Steel industry.

1. INTRODUCTION.

The top blown basic oxygen steelmaking process was developed in the late 1940s and early 1950s following the emergence of the industrial method for oxygen gas production at a reasonable price by liquefaction and distillation of air in the mid 1920s and subsequent trials with different methods of injecting the oxygen into the steelmaking vessel. Soon it became the predominant process for steelmaking. In 1995, the world total crude steel production was 748,2 million metric tons where the oxygen steelmaking processes together accounted for 59,7% of the tonnage, (~ 447 Mton).

The need for developing improved control systems has traditionally been powered by the demand for more accurate and cost efficient production. This is still a major driving force but environmental issues do also have a profound influence on this development today.

In 1996, a project "Integrated control and process design of converter processes" has been initiated in co-operation between SSAB Oxelösund AB, Royal Institute of Technology and Luleå University of Technology. The project is a part of the REGINA research programme, funded by the Swedish National Board for Technical Development (NUTEK), aiming at developing industrially relevant control systems design methods. In this paper the project objectives as well as some preliminary experimental results are reported.

2. PROCESS DESCRIPTION.

Oxygen steelmaking via the top blown converter process with its raw materials and products is schematically shown in figure 1.

2.1. Normal process course.

Scrap and hot metal are charged to the vessel and the oxygen is turned on while the lance is lowered to its blowing position. Slag forming agents are added at the beginning of the blowing period and subsequent additions can be made throughout the entire blow. Fuel, like ferrosilicon or coke, or cooling agents,
like iron oxides or shredded scrap, can be added for temperature adjustments.

By blowing the oxygen through a lance from above towards the metal surface at supersonic speed, a cavity forms where metal components, mainly Fe, Si, Mn and C, will be oxidised. Metal droplets are splashed up and

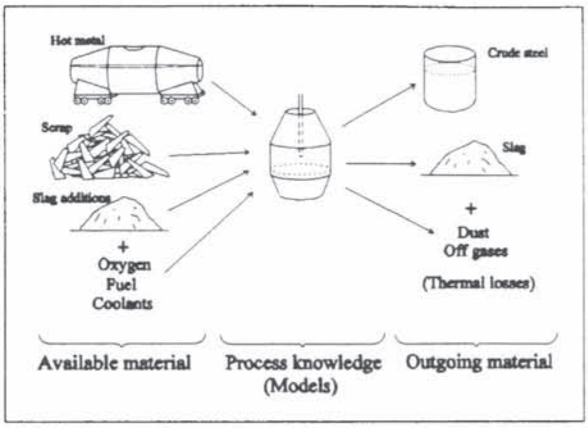

Fig. 1. The top blown converter process.

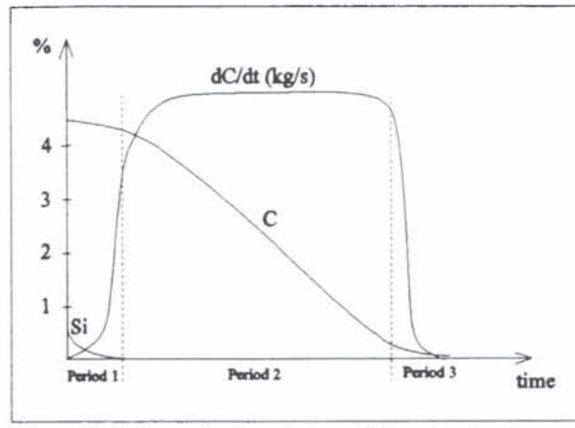

Figure 2. Schematic description of decarburization characteristics in a top blown converter.

mixed with the oxides formed and the slag forming agents added. In this mixture carbon, dissolved in the metal phase, will react with the oxides, mainly FeO, reducing it while carbon monoxide is formed:

$$\underline{C} + FeO = Fe + CO(g) \qquad (1)$$

This means that in the mixture of slag and metal a considerable gas evolution will occur resulting in a foaming slag. This foaming slag provides very large contact area between metal and slag thus assuring good conditions for typical slag/metal reactions as phosphorus and vanadium refining. The slag formation can be controlled by varying the lance height and/or the bottom gas flow rate, if such equipment is installed. The blowing period is often divided into three different periods when described.

Period 1. The first period is characterised by oxidation of mainly silicon, manganese and iron. In this first slag, lime rapidly starts to dissolve. This first period is often referred to as the slag forming period.

Period 2. When most of the silicon has been oxidised, the main decarburization period starts. During this period, from approx. 3-4 minutes into the blow until 2-3 minutes before end of blow, the decarburization rate is nearly constant and corresponding to the supply rate of oxygen.

Period 3. The final period is characterised by a rapidly decreasing decarburization rate and a rapid increase in temperature due to the heavy iron oxidation caused by the cessation of the decarburization.

The compositional changes of carbon and silicon in the metal bath during the blow are shown in figure 2 together with the variation in the decarburization rate.

2.2. *Irregularities and disturbances.*

Deviations from the desired process course can be caused by several factors. These factors may be described in four different categories; process, hardware, operator induced irregularities and production disturbances.

Process irregularities. There is a contradiction between the need to obtain high slag levels to provide good refining conditions and the desire to minimise uncontrolled slag overflow, "slopping". All events of slopping result in severe dust emissions and iron yield losses affecting the mass and heat balance computations by the control system. Furthermore, production must be stopped to allow for cleaning of the vessel mouth and the area below the vessel.

Unknown scrap dissolution rate may also interfere with process performance. Late melting of high-carbon scrap can cause uncertain composition of sample taken with a sublance resulting in erratic feed-back to the control system.

Hardware irregularities. Hot metal temperature measurements in the transfer ladle are made by means of a thermocouple and believed to be reliable. However, it remains unclear whether the measurement is representative for the total amount of the hot metal to be charged to the converter. Weighing equipment for hot metal, scrap and other additions is regularly calibrated but still has an insufficient accuracy. This influences the reliability of the model computations and estimations in the control system. The use of gas analysis in a control system is hindered by the presence of long time delays (up to 25 seconds) in the measuring system. Unknown and inconsistent wear of the furnace lining as well as the lance nozzles will also introduce uncertainties in the control system since these parameters influence the iron oxidation.

Operator induced irregularities. Most of the existing systems require control actions from the operator and therefore to some extent depend on the operator's experience and personal preferences. For instance, it is a common practice that operators add other material amounts than those recommended by the control system. It is not uncommon that the pre-set lance programs are shifted up- or downwards according to the operator's interpretation of previous heats. Furthermore, since reliable real-time measurements of the carbon content are not presently available, different operators apply different rules for deciding when to stop the blow. These operator induced irregularities make it difficult to achieve reproducible results in experimental series and undermine control system ability to optimise process performance.

Production disturbances. The converter process is only one link in a chain of unit operations from raw materials to final product. Therefore, production disturbances can change process conditions. For example, poor blast furnace performance might lead to insufficient hot metal supply or even production disruptions. Under these circumstances, more metal scrap and fuel should be used instead of hot metal to uphold production volumes. Logically, this implies changes in blowing practice.

3. PROCESS CONTROL

In order to monitor and/or control the process, different measuring systems can be employed to give feedback to either the operator or directly to existing system for automated control. These measurements can be either direct or indirect as well as with or without time delays.

3.1. Sensors.

The real-time information on the process state can be obtained from a number of sensors, see table 1. All these signals can, in principle, be used for closed-loop control.

Table 1. Sensors providing real-time information on the state of the process.

Sensor:	Information obtained:
Flow rate measurement with venturi	Off-gas flow rate.
Sound level measurement with microphone	Indication of changes in slag level.
Load cell or accelerometer on lance or vessel	Indication of changes in slag level.
Temperature measurement	Off-gas temperature.
Lance elongation	Indication of changes in slag level.
Hood pressure	Pressure difference with ambient pressure.

3.2. Actuators.

There are only a few process variables that can be manipulated by the control system or the operator - lance height, oxygen gas flow rate and purge gas flow rate. Naturally, changes in lance height are easier to measure as well as set and therefore preferable to use in a closed-loop control system. Oxygen gas flow rate should not be changed more than approximately ±5% since the nozzle is designed for a specific flow rate. On the contrary, the purge gas flow rate can be varied within a large span.

3.3. Control strategies.

Two basic approaches to control the process are; open-loop control and closed-loop control. The former assumes availability of a pre-defined control signal trajectory bringing the process to a desired state. Using the latter, measurements of the process output signals are fed back to the actuators via a controller. An obvious shortcoming of the open-loop strategy is a high sensitivity to process disturbances. Thus, a closed-loop control system of the BOS converter is sought. A major difficulty in designing such a system would be the necessity to analyse stability and performance of the closed-loop system.

The Smart Lance system developed by British Steel can be seen as a compromise between the open- and closed-loop control strategy. Control actions are made according to pre-set rules in fuzzy or rule-based systems. The general principle used by Smart Lance is shown in figure 3. After the initial slag forming period when a pre-set program is used the lance movements are determined by a fuzzy system based on off-gas analysis and sound level measurements. This control is used until the very end of the blow where the lance height again is pre-set.

Compared with conventional manual control by the operator, this system show considerable improvements with respect to slopping occurrence, iron yield and hitting rate. At the same time it is obvious that the system has some inherent drawbacks. Is designed to act as an "ideal", well-trained operator, without taking the physical and chemical laws that describe the process dynamics into account. The design of the system requires a minimum time to elapse between two consecutive control actions since it is difficult to analyse the effect of the feedback. Thus, the system is in reality an open-loop system with a decreased accuracy and possibility to counteract disturbances as a result. Several other similar systems are reported in literature (Bencini and Poli, 1993; Buydens, *et al.*, 1993; Abbatangelo, *et al.*, 1990; Takezoe, *et al.*, 1991; Pak, *et al.*, 1996; Oda, *et al.*, 1990; Funaoka, *et al.*, 1993; Kanai, *et al.*, 1997; Hatanaka, *et al.*, 1997)

3.4. Process monitoring.

The most commonly employed measuring systems, reported in literature and used for control and/or monitoring, are listed and commented in table 2. Several of these systems make use of the information obtained by the sensors listed in table 1. Off gas analysis and temperature are used for increased hitting rate with respect to carbon content while sublance is used for both carbon and temperature control. Sonicmeter, vibration measurements and camera surveillance are used for slag level control.

4. CLOSED-LOOP CONTROL OF THE BOS PROCESS.

The initial work in this project was carried out in a

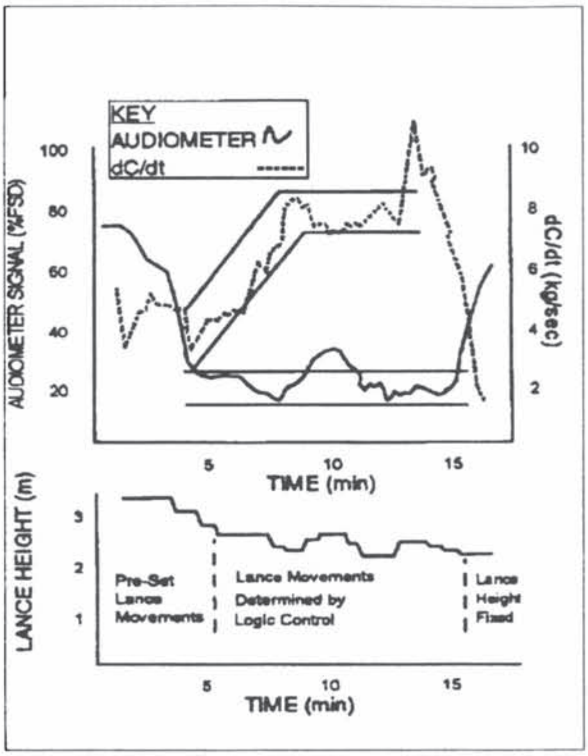

Fig. 3. Decarburization rate, sonicmeter signal and lance movements at British Steel's Teesside Plant (Smith *et al.*, 1997).

preliminary study where state-of-the-art of today was surveyed, project objectives defined and control concepts presented (Medvedev, *et al.*, 1996). A comparison was made concerning how frequently different categories of mathematical models are used in control theory and metallurgy, see table 3.

A cooperation between the two disciplines would give control engineering researchers physical models as a base

Table 3. How frequently different mathematical models are used in control theory and metallurgy.

Type of model	Control theory	Metallurgy
Static	Seldom	Often
Dynamic	Often	Seldom
Linear	Often	Seldom
Non-linear	Seldom	Often
Finite- dimensional	Often	Seldom
Infinite-dimensional	Seldom	Often
Real-time	Often	Seldom
Batch	Seldom	Often
Identified	Often	Seldom
Physical	Often	Often

for further development of control algorithms, while researchers in metallurgy gain new mathematical approaches to their modelling work.

4.1. Project objectives.

The project is aiming at integrating control theory aspects with process technical aspects in a system for model-based closed-loop control. Limitations imposed by minimum time delays between consecutive control actions and pre-set lance programs will be eliminated.

The expected practical benefits for SSAB Oxelösund AB when the control system is implemented are aimed at a;

- 90% decrease in slopping occurrence. (Today 15-20% of all heats)
- 50% decrease in re-blow ratio.
- consistent iron yield of 97%.

Table 2. Different measuring systems for control and/or monitoring and their correlation to the process.

Measuring method:	Location:	Correlation to the process:	Time delay:
Off-gas analysis	In the off-gas system.	Analysis with respect to CO and CO_2 plus measured off-gas flow rate gives decarburization rate. Carbon balance gives carbon content in metal bath.	15-25 sec.
Sonicmeter	In the hood above the converter mouth	Qualitative measurement of slag formation. Gives an indication on changes in slag level.	None
Sublance	In the metal bath	A metal sample is taken with a sampling probe. The sample is analysed and gives metal composition at the sampling moment. Also metal temperature, oxygen activity and the solidifying temperature of the sample can be measured.	Analysis: 3-7 min. Other: None
Vibration measurements	On the furnace or the lance	Qualitative measurement of slag formation. Gives an indication on changes in slag level.	None
Off-gas analysis	In the off-gas channel	Correlates to the carbon content of the metal bath due to that a decreasing carbon oxidation at low carbon content in the final stage of blowing gives a lower off-gas temperature.	In the order of 30 sec.
Camera surveillance/ image analysis	At the tap hole	The tap hole is surveyed by cameras from different angles. The pictures are compared, by using image analysis, with typical cases when slag flows out of the tap hole or not.	None

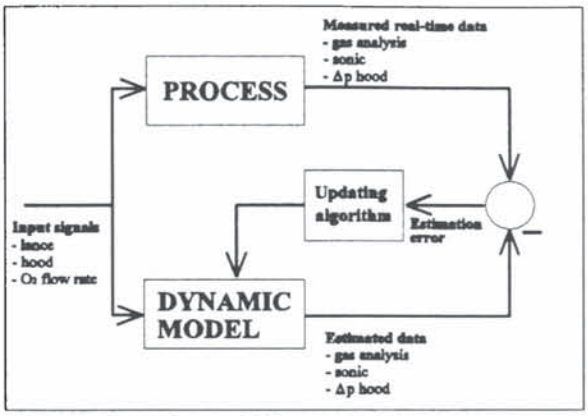

Fig. 4. A dynamic model for a converter process.

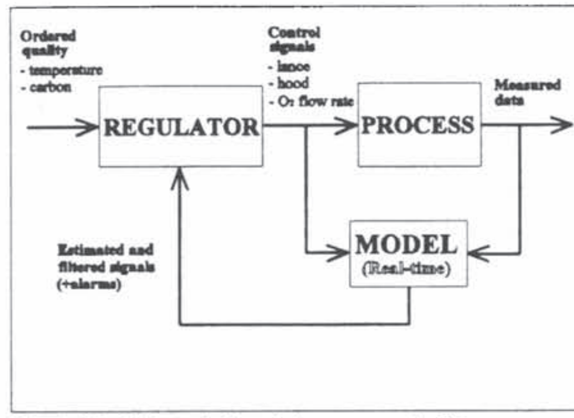

Fig. 5. Model-based closed-loop control of the converter process.

4.2. Process control and monitoring concepts.

In order to achieve the project objectives, the project has been divided in two parts:

Dynamic real-time model for the converter process. Dynamic metallurgical models for simulation of the reaction path in converters are available for stainless steelmaking in AOD/CLU converters as well as for low-alloyed steel in top-blown (BOS) converters. The models are run off-line without taking relevant real-time data into account. To be able to use these real-time data, an internal feed-back to the model of the estimation error is necessary, as shown in figure 4.

The information from the error signal can be used in at least two different ways. First, a function of the estimation error can be used as a correction signal to the process model in a way that inherent uncertainties in signals and parameter are compensated. The estimation error can also be used for adjustment of the model parameters in order to minimise the difference between measured and estimated data, i.e. parameter adaption. Both methods require an analysis of the dynamic changes in the model caused by the feed-back.

Model-based closed-loop control of the converter process. To eliminate the drawbacks with the fuzzy or rule-based systems of today, a model-based system for real-time closed-loop control of the lance movements, as seen in figure 5, will be developed. The dynamic models developed within the project will determine the design of the regulator. The control signal to the lance will be a function of the estimated state variables. Thus, the regulator can be seen as a combination of a non-linear observer and a state feed-back.

The quality (reliability) of real-time data can vary between different periods, as described previously, during the blow, and different control algorithms may therefore have to be developed for these different periods.

5. PRELIMINARY RESULTS.

In the preliminary study, two parallel experimental studies were performed. In one of these studies, metallurgical tests with slag reducing agents were done. In the other study, preliminary models for slopping detection were developed.

5.1. Slopping depressant additions.

As a direct result from the literature survey that was conducted during the preliminary study, SSAB Oxelösund decided to start trials with coke fines additions in order to depress slopping, as reported by Takezoe, et al. (1991). The preliminary results show good potential. But due to the absence of a slopping predictive system, evaluation was difficult since the additions usually were made when slopping already was occurring.

5.2. Model-based slopping detection.

In order to prevent slopping it is crucial to make an early detection of a potential slopping situation. A simple approach has been tested on logged data where the occurrence of slopping was noted.

Modelling and detection of slopping. A sufficiently good description of the slopping phenomena is given by a Hammerstein fourth order dynamic system with two input signals and one input signal. The input signals are the off-gas flow rate and the CO content in the gas. The output signal is the sonicmeter signal. A recursive estimation of the system parameters, as shown in figure 6, show that the parameters are constant before and after the slopping occurrence. The drastic changes in parameter estimations during slopping can be used for slopping detection.

As an alternative to recursive identification, two time-invariant dynamic models, of the same structure as before, has been developed. A comparison between the logged sonicmeter signal and the estimated output signals is shown in figure 7. During the time intervals when the logged signal is significantly lower than the estimated values, slopping has occurred.

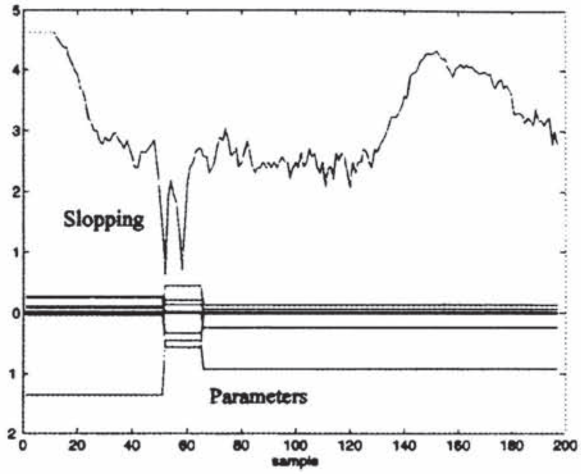

Fig. 6. Segmentation of pre-processed sonicmeter signal.

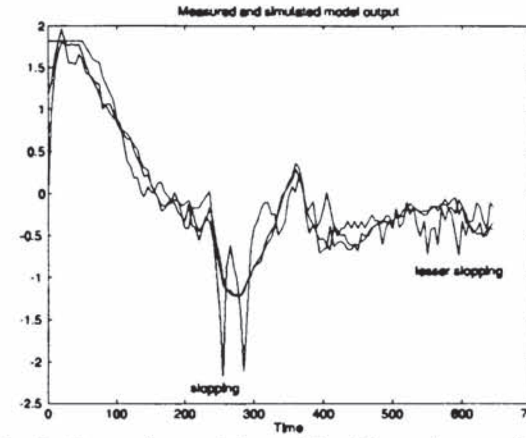

Fig. 7. Alternative model capable of detecting small slopping events.

With this method, also events with lesser slopping can be detected. However, it remains unclear whether there exists a linear model with constant parameters capable of detecting slopping events in all process conditions.

6. CONCLUSIONS.

The initial work in the project has shown that the conditions for performing a cross-disciplinary research project according to the presented concepts are good:

- Metallurgical models are available.
- Relevant real-time data is available.
- The process can be controlled manually by the operator with reasonable results.
- Simple fuzzy systems can improve the control.
- The preliminary studies have resulted in a well-established cooperation between the control engineering and metallurgical research groups as well as research and plant personnel in industry.

The preliminary results point out the importance of further pursuing the development of identified models for slopping prediction. A detailed study of the signal processing algorithm that is used with the sonicmeter should be performed. Further investigations in slopping depressant addition methods and timing should be performed since this may be an effective tool for slopping control in a future system.

7. ACKNOWLEDGEMENTS.

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8. REFERENCES.

Abbatangelo, A., M. Dalla Rena, M. Palchetti and L.Zampetti, Blowing Pattern Computerised Control at Taranto Steelshop, *73rd Steelmaking Conference Proceedings*, Detroit, Mars 1990, ISBN 0-932897-55-X.

Bencini, C. and A. Poli, Automation for Refining and Slag Control in LD Process at AFP/Piombino Steel Shop, *76th Steelmaking Conference Proceedings*, Dallas, Mars 1993, ISBN 0-932897-86-X.

Buydens, J.M., C. Marique, J. Claes, S. Knoops, E. Castiaux and M. Dutrieux, On-Line Control of the Blowing Process at Cockerill Sambre, *1st European Oxygen Steelmaking Congress*, Düsseldorf, 1993.

Hatanaka, T., Y. Arai and N. Kato, BOF EIC Integrated System at Keihin Works in NKK, *2nd European Oxygen Steelmaking Congress*, Taranto, Oct., 1997.

Funaoka, Y., H. Hirahashi and S. Kawasaki, New LD Converter Dynamic Control Using QV Analyzer at Site, *1st European Oxygen Steelmaking Congress*, Düsseldorf, 1993.

Kanai, T., A. Sakai, J Tani, S. Yoshida and N. Matsui, Development of a Slopping Prediction and Control System in BOF Operation, *2nd European Oxygen Steelmaking Congress*, Taranto, October, 1997.

Medvedev, A., P. Sjöberg, D. Widlund and R. Gyllenram, *Integrated control- and process design for converter processes*, Final report from preliminary study, November, 1996. (In Swedish)

Oda, M., M. Yoshino, Y. Muraki and T. Hasegawa, Development of the Slopping Predictive and Suppressing System in LD Converter, *Proceedings of The Sixth International Iron and Steel Congress*, 1990, Nagoya, ISIJ.

Pak, J.J., D.J. Min and B.D. Jou, Slag Foaming Phenomena and its Suppression Techniques in BOF Steelmaking Process, *79th Steelmaking Conference*, Pittsburgh, Mars 1996.

Smith, P.D., G. Harland and D. Bryce, Enhancements in Blowing Control at Teesside BOS Plant, *2nd European Oxygen Steelmaking Congress*, Taranto October, 1997.

Takezoe, H., T. Saito, K. Ebato, J. Katsuda, M. Azuma and S Hato-Guchi, Some Trials in the Development of a Slopping Prediction Technique in the BOF at Kakogawa Works, Kobe Steel, Ltd, *ISIJ International*, **Vol. 31**, (1991), No. 11, pp. 1368-1370.