EMF-timeseries analysis implemented as predictive tool in BF-tapping control

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Thermo- and electrochemical processes acting as a source of electromotive forces (EMF) in the lower part of the blast furnace (BF) have been recognized for a long time. Based on voltage acquisition at the outer furnace shell, prior research proposed the use of the EMF-transient to indirectly monitor the liquid phase content in the furnace hearth. In our investigation the amplitude and shape of the EMF signal during the tapping cycle turns out to be strongly dependent on furnace operation. Oxide melt experiments and electric potential measurements are performed in lab-scale crucibles and used together with the furnace derived EMF transients to clarify the source of the EMF signal. A model for the charge separation is developed, based on the electronic and ionic conductors involved in the redox reactions near the interfaces between hot metal, slag, solid carbon and gas phase. For model verification, the resulting resistivity network model is compared to the measured voltage response of a high temperature model cell. EMF signals at the BF are monitored at several circumferential positions on the outer steel shell and the signal-based model prediction is implemented in the process control as a melt level indicator. During tapping the drop of the melt level typically declines with increasing distance from the tap hole. The fine-structure of the EMF signal during the tapping cycle provides detailed insight into the drainage behavior and dead man dynamics.

KEYWORDS BLAST FURNACE, TAPPING CYCLES, ELECTROMOTIVE FORCE, TIMESERIES, INSTRUMENTATION, SENSOR POSITIONS

INTRODUCTION

Observations on the existence of electric currents in the BF system date back to the early 20th century. Ruff reported that a compass needle is being deflected in the vicinity of a BF. The accountable magnetic field arises from a direct current according to Biot-Savart law. Already in this early stage, scientists attributed the current source to a galvanic element inside the BF with the governing equations (I) and (II) [1].

$$FeO + C \rightleftharpoons CO + Fe \quad (I)$$

$$Fe_2O_3 + C \rightleftharpoons CO + 2\,FeO \quad (II)$$

Coke acts as the anode, iron as the cathode and the slag with varying amounts of iron oxides as the electrolyte. In addition to these theoretical considerations, Ruff reported experimental evidence regarding the validity of a galvanic cell acting as a current source. To prove this concept, an oxygen sparged fayalite melt was contacted with a carbon rod and an iron wire, which resulted in a potential difference between the electrodes. The same experiment without sparging did not exhibit a measurable voltage [1].

The signal pick-up, which is conveniently performed at the outside of the steel shell, is significantly influenced by the internal resistance network, which partially short-circuits

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the galvanic element. This resistance network reflects the operating state of the BF [1].

Dorofeev et. al. distinguish between different contributions to the overall electromotive force [2].

- Oxidation reactions of pre-reduced iron oxide and carbon in the raceway
- Direct reduction of iron oxide in the heterogeneous slag/coke layer below the tuyeres
- Oxidation of dissolved iron in the hot metal by iron oxides at the hot metal/slag interface
- Thermoelectric voltages caused by the furnace lining and steel shell

Neglecting thermoelectric effects, the net reaction from equation (I) can be split into the anodic and cathodic partial reactions (III), (IV) and (V). At this point it should be noted that the Boudouard equilibrium, which is important for the indirect (gas) reduction with CO, also represents an electron transfer reaction at the coke surface. The according electrochemical cell diagram is given in equation (VI). It is assumed that this reaction system (VI) gives rise to the majority of the net electromotive force that leads to the observed electric effects.

Anode: $(O^{2-}) + C \rightarrow \{CO\} + 2e^-$ (III)

$(O^{2-}) + \{CO\} \rightarrow \{CO2\} + 2e^-$ (IV)

Cathode: $(Fe^{2+}) + 2e^- \rightarrow [Fe]$ (V)

$Fe[C] \,|\, (Fe^{2+}) \,||\, (O^{2-}),\{CO/CO2\} \,|\, C$ (VI)

To test the validity of this working hypothesis, an experiment was carried out in which the cell was simulated. For this purpose, a graphite crucible was filled with pig iron and iron oxide-enriched blast furnace slag (BFS) and heated to 1450 °C in a radiation furnace in an inert atmosphere. In the molten state, a graphite electrode and a pure iron electrode were lowered into the melt. Care was taken to ensure that the graphite electrode contacted the slag and the pure iron electrode contacted the pig iron. In order to prevent electrical contact between iron wire and slag, the wire was guided through the slag in a corundum tube. This cell configuration is illustrated in the left part of Fig. 1. Measurements of the cell voltage range between approximately 100 – 300 mV (see result image on right side of Fig. 1). To investigate the effect of an increased reduction potential in the gas phase, CO was fed into the furnace chamber.

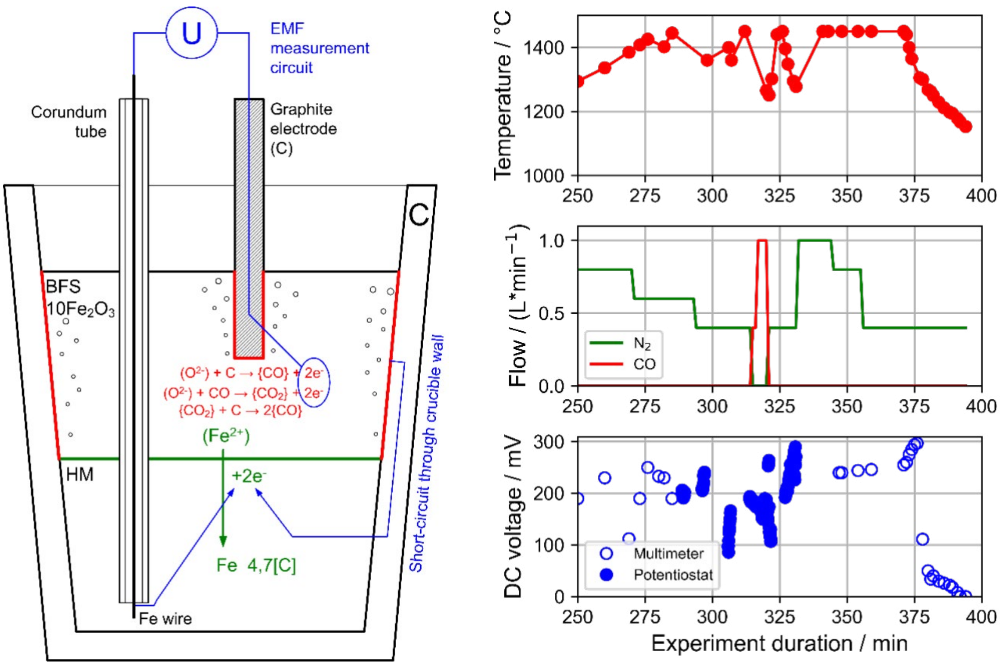

Fig.1 - left: Schematic representation of the experimental setup to confirm the existence of a measurable EMF due to the reduction reaction of iron from an iron enriched BFS into hot metal (HM). Right: Measurement results from the illustrated cell configuration; the cell is heated in a MoSi2 type, vacuum ready furnace with a free volume of approximately 30 L.

Considering anodic reaction (III) and the cathodic reaction (V), which results in the sum reaction (I), the Gibbs reaction enthalpy is ΔrG° = -112.2 kJ/mol. For reversible reactions this free enthalpy gives rise to a cell voltage of E°, according to equation (VII), involving the transfer of n = 2 electrons (F is the Faraday constant).

$$E^0 = -\frac{\Delta_r G^0}{n * F} = \frac{112.2 * 10^3 \frac{J}{mol}}{2 * 96485 \frac{C}{mol}} = 0.58\ V \qquad (VII)$$

The measured voltage, however does not reflect the true EMF because of partial short-circuiting of the cell due to parasitic currents through the crucible wall, as illustrated in Fig. 1. A similar case applies this EMF measurement at the BF, where the short circuit is additionally enhanced by the coke layer (which forms a sponge-like network in the slag as well as in the pig iron across the furnace cross-section) and by the multi-layered wall of refractory lining plus steel shell.

Measurements of the potential differences on the BF shell have a history as a predictive tool for the hearth's liquid level [3, 4]. Taking into account the resistivities of the characteristic zone of the furnace hearth (coke, slag, combustion space, refractory materials, and hot metal), Gomes et. al. [4] derived a lumped circuit element model for the electric network (Fig. 2a). However, it shall be noted that the EMF source as a simplification is localized explicitly at the hot metal / slag interface in the idealized layered illustration by Gomes et. al. (see definition of the half-cells). Contrary, in the BF a distributed EMF source may be assumed more realistically, as the coke bed penetrates the melt pool at least partially. In a different approach, Ito et.al. [3] describe a method for the hearth level prediction by application of an external electric field onto the furnace shell and measurement of potential difference (which is influenced by the inner constitution of the BF) in the sense of a 4-point (Kelvin) probing as illustrated in Fig. 2b. The Ito-approach comes with the advantage, that the signal is less affected by the thermal influence of the furnace.

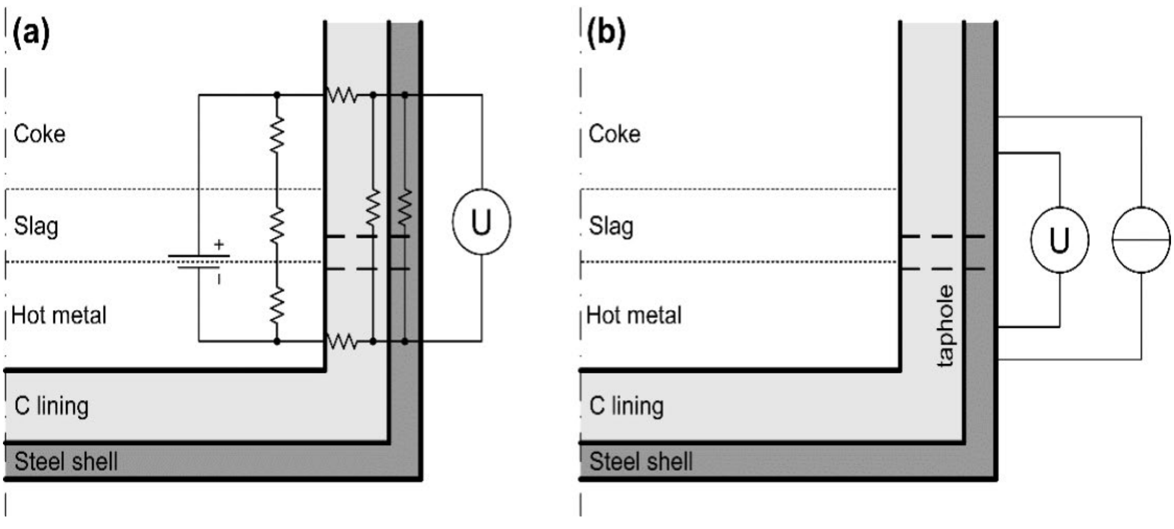

Fig.2 - Schematics of the two alternative approaches for the model circuit by Gomes et. al. (a) and Ito et. al. (b) for the evaluation of the internal electrical network.

DIAGNOSTIC APPLICATION OF EMF SIGNAL FOR BLAST FURNACE OPERATION

Observation of the EMF signal time series allows correlation with specific events during the operation of a BF, which will be described in this section. The measurement of the vertical potential difference is realized by pick-up wires made of low carbon steel, that are welded onto the furnace shell. Vertically, the welds are located below the tuyeres and at the height of the hearth floor. Laterally, four positions have been chosen in angles 9°, 63°, 171° and 297° to the tap hole (clockwise; $\phi1$, $\phi2$, $\phi3$ and $\phi4$; see insert in Fig. 3a). The signals are digitized using voltage transmitters with a measurement range of ±1.25 mV and a resolution of 16 bit. These values are recorded in the process control system, making it possible to correlate them with all other measured variables recorded there, thus enabling anomalies to be interpreted. Fig. 3 illustrates the EMF time series for four operation states. Subfigure shows the standard condition (a) as a baseline to compare with the cases of high FeO content in the slag (b), redrilling (c) and a blow-in procedure during BF-startup (d, e).

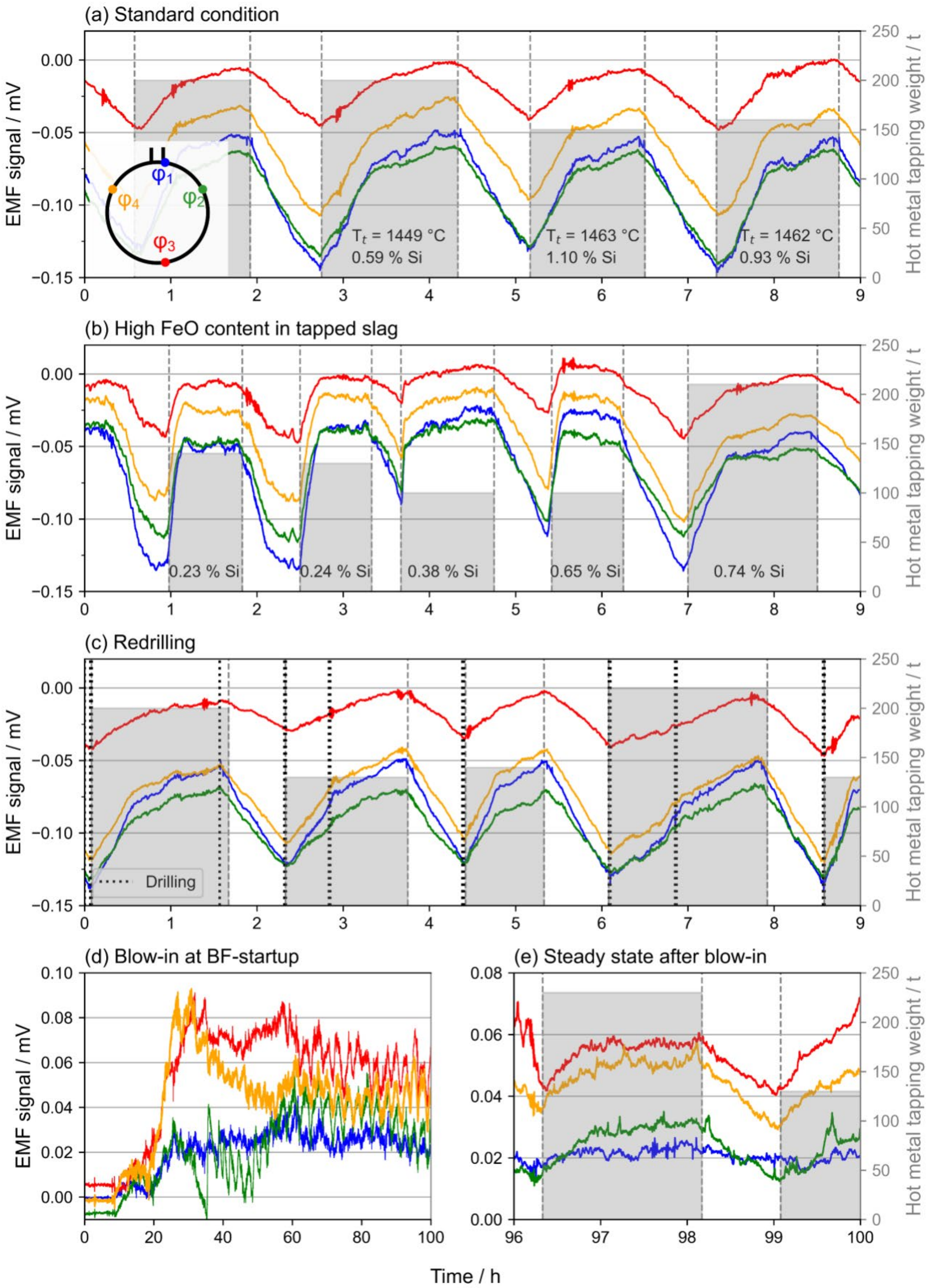

Fig.3 - EMF signal measurements on the blast furnace shell for four exemplary operating conditions at four sensors located at ϕ1 = 9°, ϕ2 = 63°, ϕ3 = 171°, and ϕ4 = 297° circumferentially from the tap hole. The grey fields mark the tapping periods and their heights indicate hot metal tapping weights. Trough temperatures Tt; hot metal silicon content in wt.-%.

A phenomenological as well as, in a first attempt, a mechanistic description of the four operation states shall be given in the following.

a) Standard condition:

During the hearth filling phase, a continuous increase in the signal's absolute value is observed. During tapping (grey fields) a two-phase outflow is indicated by the time-gradient of the signal. These phases are attributed to the outflow of hot metal and subsequently slag, respectively. However, the transition between these phases can be faded.

b) High FeO content in tapped slag:

A decrease in silicon content in the hot metal suggests that the reduction potential in the furnace is lowered.

This results in an increased iron oxide content of the slag and therefore reduced yield. The considerably lower viscosity of the FeOx-containing slag strongly affects drainage behavior. The EMF signal reflects this condition by steeper gradients during tapping followed by a saturation both during hearth filling and tapping.

c) Redrilling:

Due to tap-hole blockages (for example by coke pieces), a re-drilling can be necessary after the initial tapping start. The decision-making in this regard is currently based on the experience of a trained employee. However, a comparison of the EMF signal from a redrilled tap (at 2.8 h and 6.8 h in Fig. 3c) with a standard case shows that signal gradient during hot metal tapping is lower than during an unobstructed tapping. Including the signal in the decision-making process can therefore increase productivity.

d) Blow-in after relining:

After the heating of the hearth, iron production is started by feeding of ore. The discontinuity at 35 h is repeatedly observed during the blow-in of the BF and marks the establishment of the electrochemical redox system during the time-instant of first slag formation. The system settles into the standard condition after multiple tapping cycles.

Concluding, it can be stated that electrical measurement techniques can be beneficially applied in the blast furnace process for process control. Our studies suggest further research in the direction of impedance tomography application and fundamental research on the electrochemistry of the relevant metal/slag-reactions, as they might provide a physico-chemical basis for future smelter design.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the funding support of K1-MET GmbH, metallurgical competence center. The research program of the K1-MET competence center is supported by COMET, the Austrian program for competence centers. COMET is funded by the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, the Federal Ministry for Labour and Economy, the Federal States of Upper Austria, Tyrol and Styria as well as the Styrian Business Promotion Agency (SFG) and the Standortagentur Tyrol. Furthermore, Upper Austrian Research GmbH continuously supports K1-MET. Beside the public funding from COMET, this research project is partially financed by the scientific partner Montanuniversität Leoben and the industrial partners Primetals Technologies Austria GmbH, RHI Magnesita GmbH, voestalpine Stahl GmbH, and voestalpine Stahl Donawitz GmbH.

REFERENCES

[1] W. Ruff, Elektrizität an Hochöfen. Stahl und Eisen 47 (1927), 37, pp. 1543–1545.

[2] V.N. Dorofeev and A.M. Novokhatskii, Origin of difference in electric potentials on blast furnace shell. Steel in the USSR (1984), 14, pp. 10–12.

[3] T. Ito, J. Yotsuji and A. Nagamune, Development of Pig Iron and Molten Slag Level Measurement Technique for Blast Furnace. ISIJ Int. 54 (2014), 11, pp. 2618–2622. doi:10.2355/isijinternational.54.2618 [4] F.S.V. Gomes, J.L.F. Salles and L.A. Wasem, A new prediction model for liquid level in blast furnaces based on time series analysis. 2011 9th IEEE International Conference on Control and Automation (ICCA), pp. 772–777, Santiago, Chile (12/19/2011 - 12/21/2011), IEEE.

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