EFFICIENCY OF COPPER RECOVERY FROM A SLAG IN THE LARGE ELECTRIC FURNACE

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ABSTRACT

The electric furnace in Codelco Norte Smelter has been designed originally as slag/matte separator and slag cleaning unit. For various reasons the furnace operates as a classical slag cleaning reactor. It creates the conditions that the furnace is over-dimensioned for the amount of slag from Teniente Converter together with charged solid reverts.

Efficiency of copper recovery from a slag in an electric furnace depends on number of factors. The furnace dimensions play significant role, determining slag circulation pattern and velocity, mass transfer onto slag/coke and slag/electrodes reaction surface, inclusions coalescence and settling, and heat losses.

The complex fluid dynamic and heat transfer modeling of the electric furnace demonstrated the impact of furnace dimensions on the rate of slag reduction and copper removal as well as on unitary electric energy consumption. The results point out the optimal size of the furnace, for determine amount of processed slag and its composition.

The efficient and flexible operation of the large electric furnace, in a wide range of amount of charged slag, shows a series of limitations and requires the precise process control. Developed computer expert program is the great help in determination of optimal configuration of control parameters.

INTRODUCTION

Copper is present in a smelting slag from Teniente Converter (TC) in the form of mechanically entrained matte inclusions and dissolved copper. Copper recovery from the slag requires magnetite reduction to liberate matte inclusions and create conditions for co-reduction of dissolved cuprous oxide. Efficiency of copper recovery from the slag in an electric furnace depends on number of factors, such as slag composition and properties, forms of copper, rate of oxides reduction and slag overheating [2, 3]. The growing costs of energy carriers make the unitary electric energy consumption an important factor in process optimization.

The electric furnace in Codelco Norte Smelter was originally designed as a settler and slag cleaning unit. Thus, the furnace is a large, 13 m in diameter circular unit, equipped with three 1.0 m in diameter Söedeberg electrodes and 13.5 MVA transformer. Currently, the electric furnace operates as the slag cleaning unit, processing the liquid slag from Teniente Converter and solid reverts.

The aim of this work is the analysis of the factors determining the efficiency of slag cleaning process in the electric furnace. The analysis has been focused on the impact of the furnace size and geometry on the recovery of copper and electric energy consumption for various slags charging rate.

METHODOLOGY

Simulation of Inclusions Removal

Microscopic examination of slag samples from TC and from electric furnace allowed for determination of the size distribution of copper matte inclusions in a smelting slag as well as the size distribution of inclusions of copper matte and metallic copper in a final slag. Slag viscosity measured in PYROSEARCH Center, University of Queensland, showing the value of 0.13 Pa.s at 1250°C and 0.10 Pa.s at 1300°C (Fe/SiO_2 = 1.5) [5], was used in calculations.

The copper recovery by simple gravitational settling of matte inclusions was calculated using Hadamard-Rybczynski formula for determined slag viscosity, height and size distribution.

$$u_i = \frac{(\rho_M - \rho_S) g\, d_i^2}{12\, \eta_S} \tag{1}$$

$$Cu_S = 16.7 \sum_{i=1}^{m} n_i^o \left(1 - \frac{u_i\, t}{H}\right) d_i^3 \frac{r_M}{r_S} \tag{2}$$

The gravitational settling did not show the possibility of the decrease of copper content below 2%. Based on Tuorill concept the gravitational coalescence model has been developed. The model principle is described in details in papers [4]. The model defines the *attraction* volume, determined by the inclusion diameter and settling rate, in which the inclusion collides with smaller inclusions and their coalescence *absorbs* the smaller droplets. The effectiveness of collisions depends on the interfacial tension slag/matte. The simplified version of gravitational coalescence presents the following equation:

$$Cu_S = 16.7 \sum_{i=1}^{m} n_i^o\, e^{-\left(\frac{u_i\, \beta\, t}{H}\right)} d_i^3 \frac{\rho_M}{\rho_S} \tag{3}$$

The settling and coalescence of metallic copper inclusions produced by reduction of cuprous oxide have been analysed as well using gravitational coalescence model for determined size distribution in the final slag samples.

Measurement of Electric Parameters

The measurements of current intensity, power and power coefficient were carried out directly on the Codelco Norte electric furnace for various immersion depths of electrodes and voltage between the electrodes (tap of transformer).

CFD Modeling of the Electric Furnace

Fluidynamic and heat transfer modeling of the electric furnace has been carried out using commercial software COMSOL. Figure 1 demonstrate the 2D geometry as cross-section through two electrodes used in modeling. Simultaneous use of Navier-Stokes, heat transfer and electric charge-potential solvers permitted to determine the distribution of current, potential, power, temperature, and slag and matte velocities for various voltage and electrodes immersion.

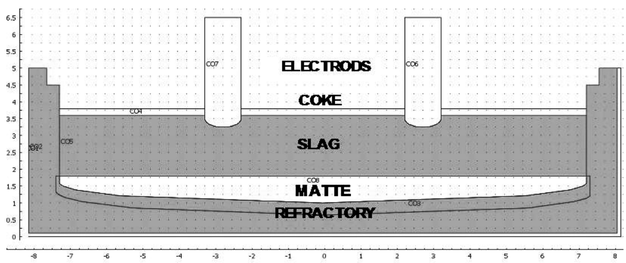

Figure 1: Geometry 2D of electric furnace used in modeling

RESULTS AND DISCUSSION

Factors Determining Efficiency of Inclusions Removal

The size distribution of copper matte inclusions is shown in Figure 2 and their mass distribution in Figure 3. It can be clearly seen that the inclusions greater than 100 μm states about 85% of matte mass. They can settle down in a reasonable time.

Calculated copper content in the form of matte inclusions versus time for gravitational settling and gravitational coalescence for presented size distribution, slag height of 1 m, slag viscosity of 0.13 Pa.s, collision effectiveness of 0.5, and assumed original copper content of 6%, is shown in Figure 4. After two hours of simple settling, the copper content in the slag lowers to about 2%. Applying gravitational coalescence model the copper content decreases to about 1%. The extension of settling time to 6 hours does not affect dramatically copper content, which decreases to 0.9%.

The participation of dissolved cuprous oxide in total copper content varies with the matte grade and particularly amount of charged reverts with high Cu_2O content. The dissolved copper varies from 10 to 20% of total copper in the smelting slag.

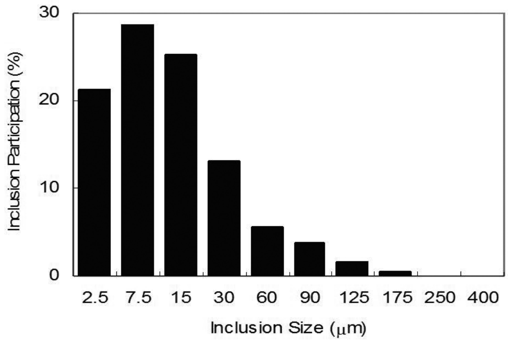

Figure 2: Size distribution of matte inclusions in TC slag

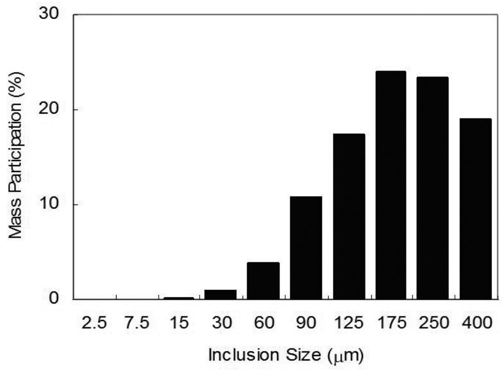

Figure 3: Mass participation of matte inclusions in TC slag as a function of inclusion size

Recovery of Dissolved Copper

The co-reduction of dissolved cuprous oxide (4) is determined by the equilibrium of reaction (5)

$$(Cu_2O)_{slag} + C \Rightarrow 2\,[Cu]_{metal} + \{CO\}_{gas} \tag{4}$$

$$(Cu_2O)_{slag} + 3\,(FeO)_{slag} \Leftrightarrow 2\,[Cu]_{metal} + (Fe_3O_4)_{slag} \tag{5}$$

The formation of fine dispersed metallic copper inclusions as the result of metallic phase nucleation makes the removal of copper very difficult. The size of copper inclusions varies from 3 to 30 μm.

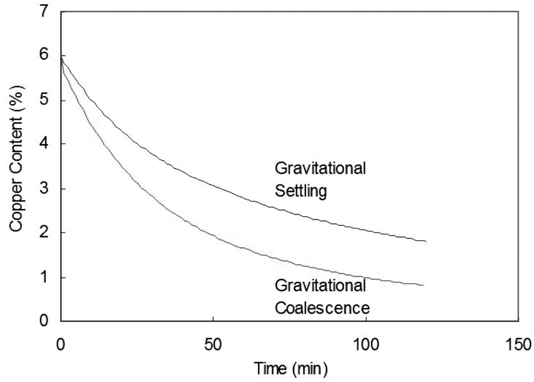

Figure 4: Calculated copper content in a slag versus time based on simple gravitational settling and gravitational coalescence model

The gravitational coalescence model did not show significant removal of metallic copper. Assuming simultaneous settling and coalescence of copper matte and metallic copper inclusions the effect of removal of metallic copper is significant.

The Role of Slag Motion in the Inclusions Coalescence and the Rate of Slag Reduction

Slag motion is induced by natural convection. The example results of the modeling presented in Figure 3 and Figure 5 show the dominating Joule's heat liberation in the vicinity of electrodes. It leads to overheating of upper part of slag, which flows towards the furnace walls and down along the walls due to decreasing temperature. The slag motion plays important role in the mass transfer, affecting the rate of magnetite reduction at the slag/electrode and slag/coke surfaces. The results presented in papers [1, 3] clearly showed the strong dependence of power input on the rate of reduction. Depending on the electrode power density the temperature at electrode/slag interface can be from 100 to 300°C higher than slag temperature. It creates intensive slag motion. The large furnace size limits this motion due to the distance to the side walls where slag is cooled down and moves along slag/matte interface (Figure 6).

Slag motion affects as well the inclusions coalescence and removal. Presented gravitational coalescence model describes only the simple case of inclusions interaction due to vertical movement. Smaller matte and metallic copper inclusions (<50 mm) can be treated as an emulsion of the matte and metal in a slag, which cannot settle down. Thus, any slag motion induced by natural convection will increase the probability of inclusion collisions, destabilizing the emulsion.

The furnace size and amount of processed slag and reverts affects the pattern and velocity of slag motion. The power input is limited by the increase of slag temperature up to 1300°C determined by the refractory lining. Thus, if the residence time of slag is long because the low charging rate of a liquid slag and solid reverts, the power input decreases and the slag motion slows down.

The slag temperature (Figure 7) tends to form steep vertical gradient, what illustrates Figure 8.

The temperature gradient causes the magnetite stratification and formation of magnetite and copper reach layer at interface with copper matte disturbing phase separation.

Figure 5: Distribution of power input

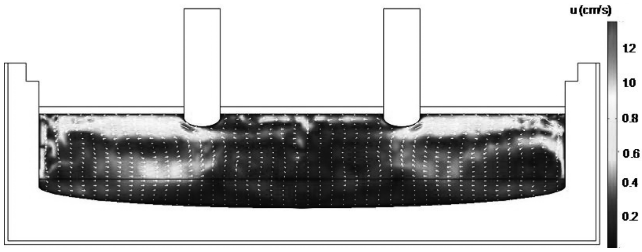

Figure 6: Distribution of slag and matte velocity

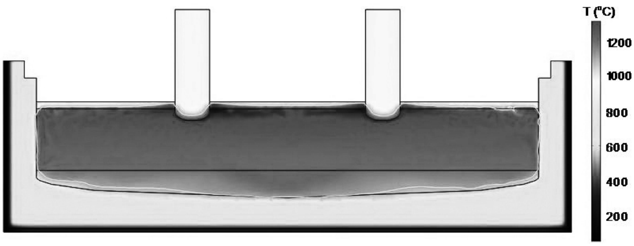

Figure 7: Distribution of temperature

The vertical temperature gradient grows rapidly with height of the slag layer. Thus, in large electric furnace the high slag layer requires deeper electrode immersion or higher power input putting the slag in intense motion. In the case of Codelco Norte electric furnace deeper electrode immersion leads to fast increase of current intensity and the sharp decrease of energy efficiency due to the slag high electric conductivity. Therefore, an intensive processing of large amount of slag with high power input can assure the efficient operation. The increase of amount of reverts allows for the increase of power input. However, processed reverts should have low content of cuprous oxide.

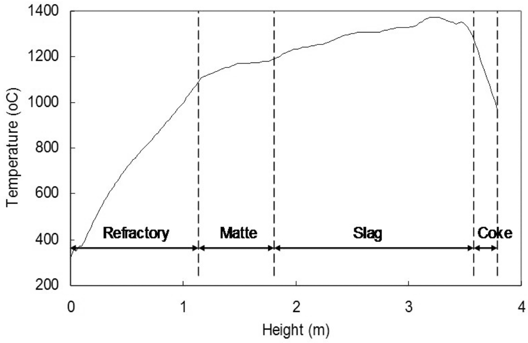

Figure 8: Distribution vertical of temperature in furnace centre

Energy Efficiency

Transformer properties determine maximal current and voltage/current ratio as a function of electrode immersion and slag electric conductivity. Power of three phase transformer is define as:

$$P = \sqrt{3}\, U\, I \cos \phi \tag{6}$$

With the growing depth of immersion and current intensity the growing angle between voltage and current results in the power decrease. The results of measurements of power as a function of electrode immersion for various tap (voltage) are shown in Figure 9.

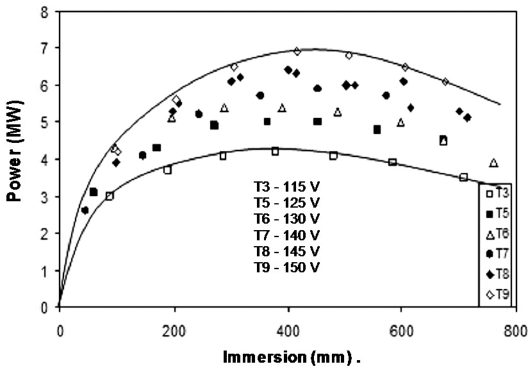

Figure 9: Power input versus electrodes immersion for various voltage between electrodes

The power coefficient which it is shown in Figure 10 decreases linearly with the immersion depth of electrodes in a wide range of voltage. The dependence demonstrates the dramatically growing energy losses with the growing depth of immersion. It depends strongly on the slag electric conductivity. The measurements of electric conductivity by PYROSEARCH [5] showed very high conductivity of the synthetic slag close in composition to Codelco Norte slag from Teniente Converter (220 – 300 S/m at 1250-1300°C).

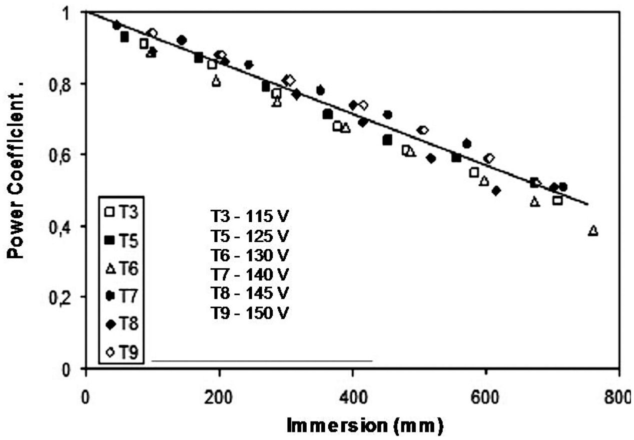

Figure 10: Power coefficient versus electrodes immersion for various voltages between electrodes

The modeling results for above electric conductivity are in good agreement with the measurements presented in Figure 9 and Figure 10, explaining the high energy losses. Therefore, the observed tendency for the electric furnace operation at high current/low voltage configuration resulted in low energy efficiency of the process.

The Role of Electric Furnace Size for Determined Slag Charge

The average charging rate of the electric furnace with a liquid slag and solid reverts determines the slag residence time and unitary consumption of electric energy.

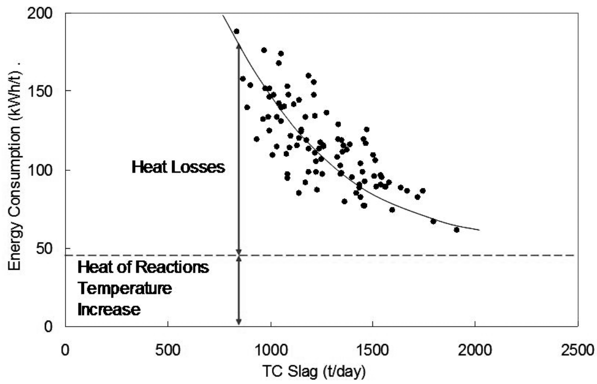

Figure 11: Unitary electric energy consumption versus rate of daily slag charge

Assuming that there is no charge of solid reverts, typical decrease of magnetite content from 16 to 8% and the increase the slag temperature about 30°C, the unitary energy consumption is equal approximately 45 kWh/t of slag. If the charge rate of a liquid slag is small the total unitary consumption is high due to long residence time and high participation of furnace heat losses in the unitary energy use. The graph in Figure 11 presents the operational data and a trend line. For example, the increase of the amount of processed slag from 800 t/day to 2000 t/day results in the decrease of unitary energy consumption from 180 to 65 kWh/t.

Expert System for Electric Furnace Control

Analyzing the optimal operation of the electric furnace from point of view of copper recovery and minimization of electric energy consumption the computer program was developed as an expert tool for furnace operators. The program appearance is shown in Figure 12. After introducing the current parameters the operator is defining the required temperature of slag and matte, and the time the values should be achieved. The system is defining the optimal configuration of voltage (tap) and electrode immersion.

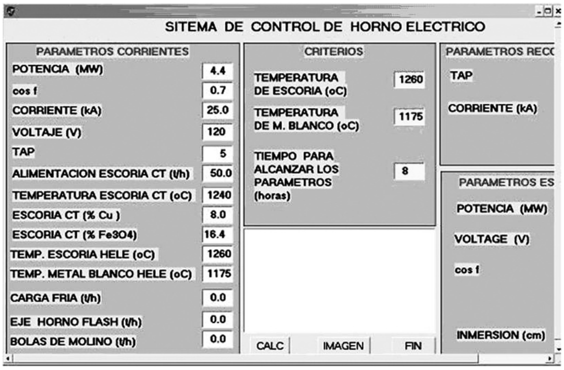

Figure 12: Computer expert system of electric furnace control

CONCLUSIONS

The efficiency of copper recovery from a smelting slag in an electric furnace depends on slag properties, forms of copper and operating parameters of the furnace.

The furnace size and geometry for determined amount of processed slag plays an important role, affecting copper recovery and energy efficiency. The planned intensification of smelting rate of Teniente Converter should result in the decrease of copper content in the waste slag and unitary energy consumption.

Important role in inclusions removal plays the slag motion induced by natural convection, which affects the rate of slag reduction and enhances the mass transfer towards the coke and electrodes.

The slag motion depends on the power input and furnace geometry. Intensity of power input is limited by the highest slag temperature acceptable for refractory lining and slag residence time.

Energy efficiency of slag cleaning grows with the growing voltage/current intensity ratio and decreasing slag residence time.

NOMENCLATURE

Cu_S = copper content in slag in the form of inclusions, %
d_i = inclusion diameter fraction size *i*, m
g = gravity acceleration, m s^{-2}
H = slag height, m
I = current intensity, A
n_i^o = number of inclusions in original slag size fraction *i*, m^{-3}
n_i^t = number of inclusions after time *t* in size fraction *i*, m^{-3}

P = power, W
u_i = velocity of inclusion fraction size *i*, m s^{-1}
U = voltage between electrodes, V
t = time, s
$\cos\varphi$ = power coefficient,
β = effectiveness of inclusions collision,
ρ_S = slag density, kg m^{-3}
ρ_M = matte density, kg m^{-3}
ηS = slag viscosity, Pa·s

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