QUANTITATIVE METHODS FOR COPPER SMELTER REENGINEERING PROJECTS

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ABSTRACT

The quantitative techniques to evaluate the enhancement of a particular unit operation should consider the corresponding changes to the adjacent unit operations. For example, the expansion of offgas handling capacity should consider the corresponding changes in converter cycle times, matte grade, and other operational parameters, that can provide the optimal system-wide benefit.

In general, the upgrading of smelter equipment is risky due to the size of capital investment, as well as any unforeseen impacts on rest of the operations. However, this risk can be mitigated by applying the principles of Front End Loading (FEL) in the formulation of multiphase reengineering projects. The initial phases of engineering are relatively inexpensive, and determine whether or not to pursue the subsequent phases that are comparatively more expensive. Each phase of engineering depends on increasingly detailed descriptions regarding the critical phenomena that can effect design decisions; the increasing levels of detail may result from numerical simulations, as well as laboratory and plant trials. The quantitative framework should be sufficiently flexible to accommodate these increasing levels of detail, regardless of the particular phenomena, so that it may evolve throughout the project.

The current article describes the combined usage of mass balancing, thermochemistry and multiphysics, in the development of discrete event simulation (DES) and finite differences (FD). The incorporation of finite differences into a DES framework depends on adaptive time-stepping, to determine threshold-crossing times, e.g. when the matte temperature surpasses a critical level that necessitates the addition of cold charge. The hybridization of DES and FD is appropriate for multiphase smelter development projects, as it supports semi-continuous material flows, operational policies and scheduling, as well as unexpected events and trends, in increasing levels of detail. This type of framework will support the installation and tuning of modern control systems, including state-of-the art sensors and machine learning algorithms.

KEYWORDS

Continuous Improvement, Discrete Event Simulation, Front End Loading, Finite Differences, Multiphysics, Peirce-Smith Converting, Slag Cleaning Furnace, Thermochemistry

INTRODUCTION

Following the advent of Peirce-Smith (PS) batch converting in 1909, copper sulphide smelters underwent a series of incremental improvements throughout the twentieth century (Price, Harris, Hills, Boyd, & Wraith, 2009; Devia, Parra, Queirolo, Sánchez, & Wilkomirsky, 2019), including the implementation of tonnage oxygen (Kapusta, 2017), and innovations in heat transfer and offgas handling equipment (Treilhard, 1972; Navarra & Mucciardi, 2018; Taskinen, Akdogan, Kojo, Lahtinen, & Jokilaakso, 2019), as well as sensors (Arias et al., 2018). Conventional smelter designs continue to have a dominant world presence (Figure 1a), although alternative approaches have emerged that feature continuous converting (Cui et al., 2018; Hogg, Nikolic, Voight, & Telford, 2018; Wang & Guo, 2018), as depicted in Figures 1b, 1c and 1d. Figure 1a considers the antiquated reverberatory furnaces mainly for their historical significance (Noorossana et al., 2012), as this technology has been replaced by bath and flash furnaces (Parameswaran, Wilhelm, & Camorlinga, 2018). Even with the significant advancements in copper smelter technologies, however, strict environmental regulations complicate the opening of new smelter locations, particularly in countries that already have a mature copper sector (Devia et al., 2019); the copper industry is thus pressured to reengineer their existing smelters, so that they may remain competitive with the newer smelters.

Copper smelters undergo cycles of development that include one or more continuous improvement projects, which are punctuated with large-scale reengineering projects (Figure 2). Data is accumulated throughout regular operation (Ferrer et al., 2018), which compliments the observations that are made by operators and engineers, and support hypotheses for improved operation. Many of these hypotheses may be easy to test, presenting low risk and small expenditures that are within operational tolerances and budgets.

Most smelters have a team that is devoted to continuous improvement (CI) projects (or “special projects”, or the like) with the authority to formulate and test hypothetical improvements, and subsequently to implement changes that span several unit operations and/or administrative departments. Suggestions for improved operations are encouraged (or incentivized) to come from smelter employees, and submitted to the continuous improvement team, so that they may be considered within continuous improvement projects. This approach allows, for example, the standardized blending of feed stockpiles (Navarra et al., 2019) and the optimization of production scheduling (Navarra, 2016), leading to predictable converter cycle times (Navarra, Kuan, Parra, Davis, & Mucciardi, 2016). By ensuring a stable flow of material and the reliable transmission of information (Ferrer et al., 2018), CI projects can increase the utilization oxygen supply and offgas handling equipment (Navarra, Parra, Davis, & Mucciardi, 2015), thereby decreasing the operational expenses and effectively increasing smelter capacity.

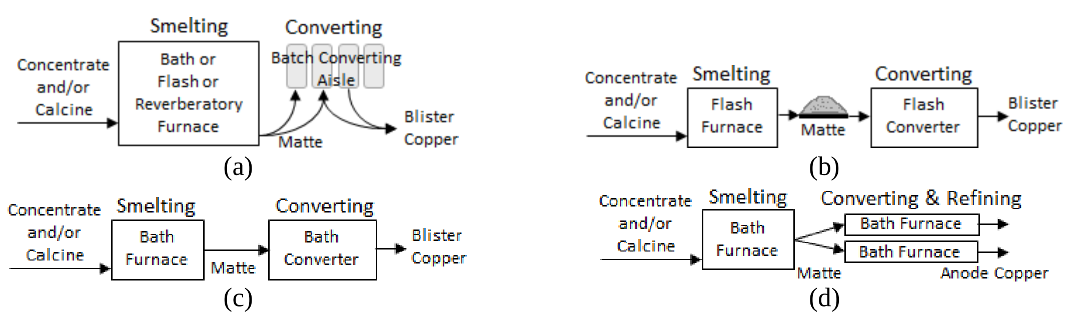


Figure 1. Smelting and converting operations within copper smelters: (a) Conventional Design featuring Peirce-Smith Converting Aisle, (b) Kennecott-Outotec Double-Flash, (c) SKS Bottom-Blowing, (d) Dongying Fangyuan Two-Step Anode Production

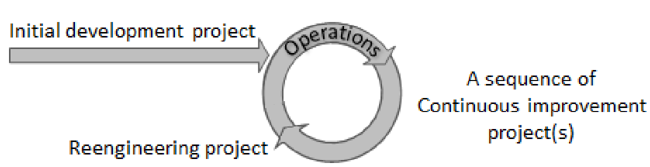


Figure 2. Cycle of continuous improvement and reengineering

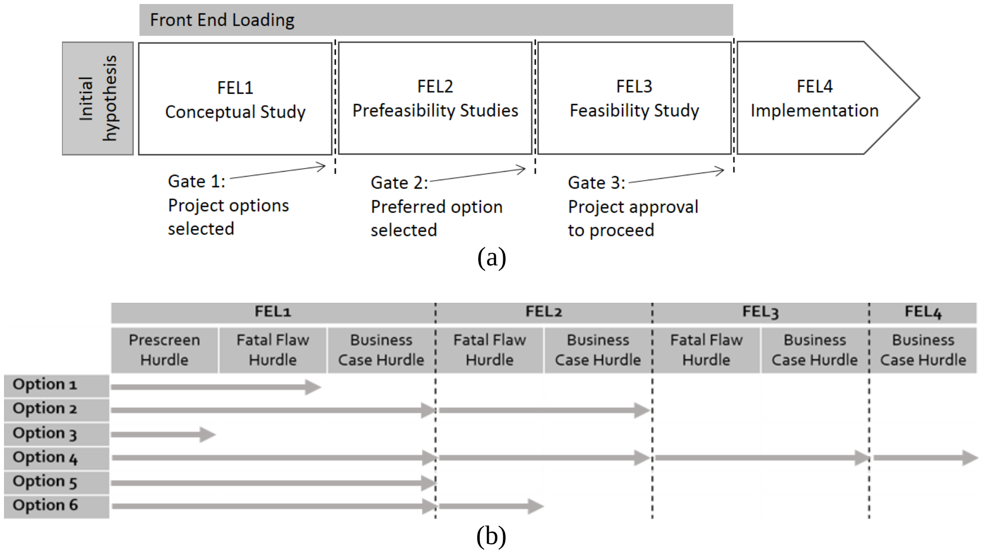


Figure 3. FEL multiphase engineering project: (a) FEL phases and gate reviews (Young & Wheeler, 2015), (b) Elimination of design options (McMeekin, Twigge-Molecey & Blake, 2015)

CI projects may address the misalignment of different unit operations or departments, either within the smelter, or reaching out to external providers. It is therefore important for the CI team to create consensus among the relevant parties. For example, the adjustment of the offgas handling system must consider the corresponding changes in converter cycle times, matte grade, and other operational parameters (Navarra et al., 2016), that will result in an optimal system-wide benefit. Cross-organizational interaction allows smelters to continually learn and improve their operations, so that they remain competitive. The continuous improvement team should maintain an active communication with the human resources department, to identify critical gaps in expertise that can be resolved through in-house professional development. The strategic development of in-house expertise can be an advantage for a mature smelter, and can increase employee job satisfaction.

Moreover, a smelter must foster groups of individuals that have knowledge of the system limitations, hence an understanding of which combinations of equipment could eventually be upgraded as part of a reengineering project. The upgrading of smelter equipment is risky, however, as it implies large capital investments (potentially hundreds of millions of dollars), and the impacts on desperate unit operations may not be initially understood. This risk can be mitigated by applying the principles of Front End Loading in the formulation of multiphase reengineering projects (Young & Wheeler, 2015), as illustrated in Figure 3.

The initial phase of a reengineering project (FEL1) benefits from the accumulated experience and observations of the smelter staff, including the CI team. This initial phase is relatively inexpensive and may be comparable to a continuous improvement project; this phase is known as the scoping study, and establishes several competing design options to be considered for prefeasibility studies (FEL2). The prefeasibility studies might require external consultants, and typically require expenditures that exceed normal operating budgets. FEL2 determines which design option is most favourable, and is most likely to address the technical needs of the smelter. In particular, FEL2 must detail the potential interactions between unit operations, thus detailing the comparative advantages of the competing design options; however, several options may fail the gate review due to technoeconomic hurdles (Figure 3a). Subsequently, the budget and external expertise required for FEL3 is extensive (potentially millions of dollars), and is usually concentrated on one single option (Figure 3b); this includes detailed engineering, and possibly pilot plant studies (McMeekin, Twigge-Molecey, & Blake, 2015). The final gate review includes the "go-no go" decision, whether or not to implement the series of capital intensive changes to the smelter (FEL4). In summary, the Front End Loading structure addresses the initial hypothesis for improvement (a.k.a. "the initial business case"; see McMeekin et al, 2015) in successive phases that require increasingly larger amounts of resources, but successively reduces the risk of detrimental or overly expensive changes to the smelter.

CI and reengineering projects depend on quantitative tools to assess the potential benefits of proposed changes to the operation. Indeed, many of the tools that are created during CI projects, are further adapted and used in the various stages of reengineering, especially the gate reviews. Moreover, the various copper smelter designs (Figure 1) are based on similar underlying thermochemistry, which fosters a common set of tools that can be developed as a starting point for all copper smelters (Coursol & Mackey; Navarra, Marambio, Oyarzún, Parra, & Mucciardi, 2017). As described in the following section, a hybridization of Discrete Event Simulation (DES) and Time-Adaptive Finite Differences (TAFD) provides an appropriate framework for copper smelter reengineering projects; DES-TAFD hybrids support the semi-continuous dynamics of conventional PS converting (Figure 1a), as well as the thermochemistry and material flows that are common to all copper smelters (Figure 1).

OPERATIONAL DYNAMICS OF THE SLAG-FORMING REACTION

The system-wide quantification of copper smelters is founded on mass balancing, determining the tonnages of oxygen and fluxing agents required for a given extraction rate of Cu from chalcopyrite $CuFeS_2$, bornite Cu_5FeS_4, chalcocite Cu_2S, and other copper-containing sulphides. The earliest phases of a CI or reengineering project may rely on static mass balances. However, a common complication arises when confronting the slag-forming reaction:

$$\mathrm{FeS_{(matte)}} + \left(\frac{6+7\alpha}{4+4\alpha}\right)\mathrm{O_{2(blast)}} \rightarrow \mathrm{FeO}_{\left(\frac{2+3\alpha}{2+2\alpha}\right)\mathrm{(slag)}} + \mathrm{SO_{2(offgass)}} \quad (1)$$

in which α is the degree of oxidation of the slag; the completion of the mass balance requires an estimation of α, as described below. The slag-forming reaction (Equation 1) begins within the smelting furnace, and is completed within the converters (Figure 4), as determined by the matte grade.

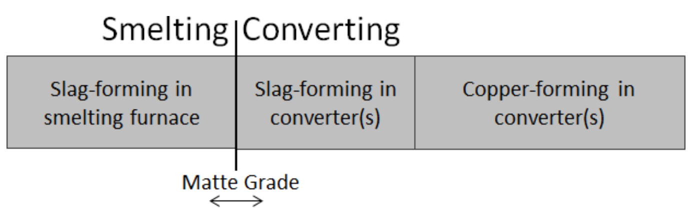


Figure 4. Repartition of slag-forming and copper-forming reactions between the smelting furnace and the converter(s)

During a conventional PS converting cycle, there are several repeating charge-blow-skim segments (Tan, 2009), resulting in the removal of iron-bearing slag. Following the final skimming, the remaining de-ironed matte is known as "white metal", consisting of Cu_2S. This white metal is subject to the copper-forming blow (Schlesinger, King, Sole, & Davenport, 2011a), resulting in blister copper (≈ 99% Cu) that undergoes fire refining to produce anodes (≈ 99.5% Cu), which are subsequently transferred into electrorefinery to produce cathodes (≈ 99.99% Cu); as depicted in Figure 1d, the Dongying Fengyuan process combines converting and fire refining into a single process (Cui et al., 2018). A static mass balance does not capture the individual charge-blow-skim actions of conventions converting (Figure 1a), nor does it capture the batch-wise production of copper anodes that is typical of all copper smelters (Figure 1).

The degree of oxidation α is the ratio of ferric to ferrous ions (Fe^{3+} /Fe^{2+}) within the slag; α = 0 corresponds to wustite FeO, whereas α = 2 corresponds to magnetite $FeO_{4/3}$ commonly written as Fe_3O_4. For fixed oxygen flows (be it in smelting or in converting), α completes the mass balance, thus determining the production rate of the smelter (Navarra et al., 2018a; Navarra, Lemoine, Zaroubi, & Marin, 2018b). It may be sufficient to assume a fixed value for the early stages of a reengineering project (typically α = 0.15), but this does not represent the coupling of α with the bath temperature *T*, nor does it consider the importance of slag composition. A high α value is associated with high slag viscosity, which leads to matte entrainment into the slag, resulting in copper losses. (The risk of Cu_2S entrainment is highest as the converter approaches the transition between slag-forming and copper-forming. The risk is especially high toward the end of the refractory campaign life due to poor mixing conditions). Depending on the propensity for entrainment, several strategies can be employed by smelters avoid these losses, or to reprocess the slags (Schlesinger et al., 2011a). The following section discusses slag cleaning furnace.

In practice, slag composition is controlled through the addition of flux; the operational parameter most closely associated with slag composition is the SiO_2/Fe mass ratio within the slag. The classical model developed by Goto assumes fayalitic slag (Goto, 1974; Kemori, Kimura, Mori, & Goto, 1987), and has recently been adapted by Navarra et al. (2018a, 2018b), applying Newton's Method to simultaneously calculate T and α, as a function of common operating parameters, including SiO_2/Fe ratio, matte grade, oxygen enrichment and oxygen efficiency; the calculation of α, allows the completion of the smelting furnace mass balance, which has relevance for production scheduling, and the utilization of oxygen supply and offgas handling (Navarra et al., 2015). A similar approach could also be developed for calcium ferrite and olivine slags (Schlesinger et al., 2011b). Moreover, thermochemical databases can be linked to Discrete Event Simulation (DES) frameworks to describe and control the dynamic partitioning of minor elements (Klaffenbach, Alvear, Guo, & Blanpain, 2018; Navarra et al., 2018b); this may be the subject high-impact CI projects that are comparatively inexpensive.

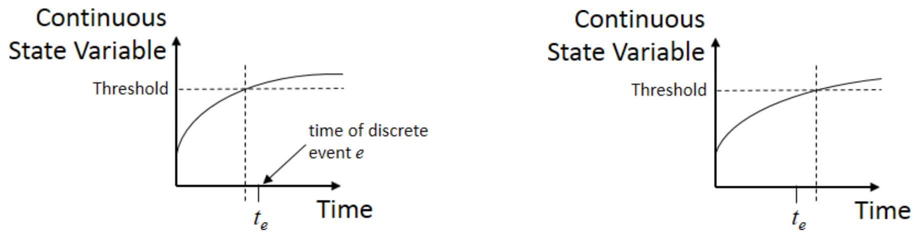
It may be practical to calculate a single smelter-wide α that aggregates the slag-formation throughout the smelting and converting furnaces. However, these furnaces present different operating conditions, hence the separate consideration of α_{Smelting} and $\alpha_{\text{Converting}}$, describing smelting slag and converting slag, respectively. In typical copper smelters, the smelting furnace provides a buffer against upstream variation, whereas the converters are operated as a bottleneck (Navarra et al., 2016); $\alpha_{\text{Converting}}$ is thus a direct indicator of overall smelter production, if taken in the combination with the (average) converter slag-forming blast rate and oxygen enrichment, and the (average) copper-forming blast rate and oxygen enrichment; more detailed studies may consider the oxygen efficiency (i.e. the fraction of oxygen that reacts with the bath, rather than passing directly into the offgas), under different smelting and converting conditions.

Particularly for batch converting (Figure 1a), there can be several segments of charge-blow-skim, each featuring different thermochemical conditions, hence different values of α for each segment (Tan, 2009). For instance, a smelter operational mode that employs cycles of n converting segments, may be described by the sequence $\{\alpha_{\text{Smelting}}, \alpha^1_{\text{Converting}}, , \alpha^2_{\text{Converting}} \ldots, \alpha^n_{\text{Converting}}\}$, in which $\alpha^i_{\text{Converting}}$ is the degree of oxidation of the slag that is skimmed at the end of the i^{th} segment. Each of these values may be the result of finite difference (FD) calculations, similar to that of Kyllo et al. (Kyllo & Richards, 1991). Beyond the conventional smelter design of Figure 1a, a sequence of α's can describe operational modes for continuous converting (Figures 1b, 1c and 1d), in which a sequence of different slag chemistries are skimmed during both smelting and converting, perhaps to optimize the balance between throughput and entrainment losses.

A mode of operation (a.k.a. "operational mode") is, in general, defined by:

- Expected mass and information flows
- Controlled, standardized and/or *ad hoc* responses to unexpected events and trends

In a typical smelter operational mode, a predetermined matte grade defines how much of the slag-forming reaction is performed in the smelting furnace, and how much must then be performed within the converting stage (Figure 4). Indeed, a higher matte grade implies that more of the slag-formation is done in the smelting furnace; typical matte grade values for bath and flash smelting are given in (Navarra et al., 2016). The matte grade, along with other operational values (final smelting temperature, number of ladles, quantity of cold charge, etc.) determines the initial bath conditions within the first charge-blow-skim segment of a PS converting cycle; following the final charge-blow-skim segment, the bath composition is approximately that of Cu_2S. However the intermittent conditions that would determine when to skim (thus determining the $\alpha^i_{\text{Converting}}$ values), may depend on when the critical thresholds are reached for state variables such as bath temperature, bath volume, as well as slag composition values (Figure 5); these types of specifications are critical features that define the operational mode.



(a) (b)

Figure 5. Threshold-crossing event in relation to another event *e*. Time-Adaptive Finite Differences determine if the threshold is crossed (a) before *e*, or (b) after *e*.

Under a given operational mode, the decision to take one action instead over another depends on when the threshold-crossing events occur, in relation to another events (Figure 5). For example, if a converter exceeds a certain temperature at a certain point during the slag-blowing reaction, preparations should be made so that additional cold charge can be inserted after the next skimming action. Otherwise, a different sequence of actions can be taken, which will conserve the cold charge.

Time-Adaptive Finite Difference (TAFD) are an essential feature of the most recent smelter computational frameworks, allowing the placement of threshold-crossing events in relation to other events (Figure 5), within the virtual timeline. In particular, Navarra et al. (2018a, 2018b) apply the Runge-Kutta-Fehlberg method that compares fourth and fifth order finite difference formulations (Butt, 2010); Newton iterations are nested within these time steps to simultaneously calculate T and α, and then to complete the heat and mass balances. An attempted step is only accepted if the fourth and fifth order estimates give sufficiently close estimates of T and α, otherwise a smaller time step is attempted. Each attempted time-step is able to use the previous results of T and α, as a starting point for the Newton iterations, so that the computation is relatively efficient. Indeed, it is possible to simulate hundreds of operating days within a matter of hours.

The detail with which smelter operational modes are analyzed depends on the nature of the project, as well as its stage of development; for example, it is not recommended to explicitly represent ladle-crane motions in a Discrete Event Simulation (DES) model, except in the later stages of a project whose benefits are constrained by the availability of cranes and ladles (Coursol & Mackey, 2009). Nonetheless, typical smelter improvement projects, should benefit from operational slag data to complete the mass balance for smelting and converting, thus to compute α. A comprehension of α is important for any large-scale changes that would inevitably alter the mass flows, and thus modify the modes of operation. In case the slag chemistry data is not immediately available, Goto's model (Goto, 1974) can be applied, following the aforementioned treatment of Navarra et al. (2018a; 2018b).

Within a CI projects, hypothetical changes to the operational modes can be tested using DES models. This includes changes in operational scheduling (Navarra, 2016), considering that the execution of a scheduling algorithm is itself a discrete event. Depending on the smelter, each scheduling period may correspond to either 12 or 24 hours. The state of the smelter at the end of one scheduling period, constitutes the initial condition for the next scheduling period; thus a DES model can simulate hundreds of operational days. During a particular scheduling period, there may be an unexpected event, such as an equipment breakdown (Campbell, Reed, & Warner, 2013), or a delay in the arrival of concentrate due to logistical complications (Navarra et al., 2017).

Mature smelters should develop and continually improve a dynamic framework that can facilitate CI projects and eventual reengineering projects. In particular, a DES-TAFD framework can link the bath chemistry of individual charge-blow-skim segments of PS converting cycles to the overall smelter dynamics, including plant logistics and scheduling. A well-developed simulation framework can be a starting point to evaluate potential operational and technological changes within the smelter, in relation to the main elemental and economic flow streams.

The FEL approach determines which specific aspects should be the focus of intensive computational and experimental studies (McMeekin et al., 2015). Moreover, the formulation of operational modes describes how these specific aspects are connected to the adjacent unit operations, and to the overall functioning of the smelter (Navarra et al., 2017). In particular, smelter engineers are justifiably reluctant to alter converter slag chemistry, because they are uncertain about the corresponding changes that should be implemented within the slag-cleaning to avoid copper losses (Schlesinger et al., 2011c). Indeed, an electric slag-cleaning furnace features multiphysical coupling, including thermochemical and electrothermomechanical phenomena (Marin, 2015a).

Slag-cleaning furnaces must be operated within a physicochemical regime in which the refractory lining is protected by solidified layer of slag. This minimizes chemical erosion of the refractory walls and also reduces the risk of mechanical damage due to thermal cycles inside the furnace. However, the formation of the protective layer depends on the capacity of the wall cooling system. Within the early stages of a reengineering project, it may not be clear if the existing cooling system is adequate for a newly proposed operational mode. Mutliphysics finite element simulations mitigate the risks associated with smelter reengineering projects, for example, by computing systems of partial differential equations for critical process equipment; in the case of slag-cleaning, Marin (2006, 2015a, 2015b, 2016) considers a coupled system of equations including heat transfer, fluid flow, thermodynamic equilibrium, and phase change, as well as electric and magnetic potential (Figure 6).

Marin's slag-cleaning model is implemented within the software COMSOL Multiphysics, utilizing the proprietary M4Dlib external library that is compatible with the FactSage-Family of thermodynamic databases (2015b). The model considers a slag layer heated by applying electric current through two electrodes located at the surface of the slag. The passage of electric current generates heat within the slag by means of Joule heating, while simultaneously inducing a magnetic field inside and around the slag domain. The cross product between electric current density $\vec{J}$ and magnetic field $\vec{B}$ creates a body force called the Lorentz force (Griffiths, 1999) this drives intensive stirring of the slag layer (Figure 6). Convective flow currents bring hot slag from the electrode zone towards the furnace wall, where heat is drawn (Figure 7). An outer protective layer of solid slag is formed only if sufficient heat can be removed by the cooling system.

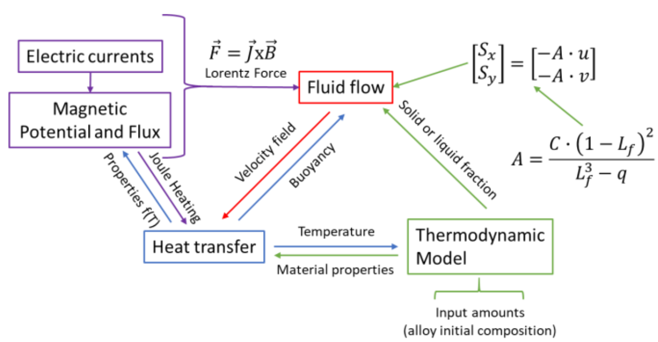


Figure 6. Outline of a multiphysics model of electric slag-cleaning furnace

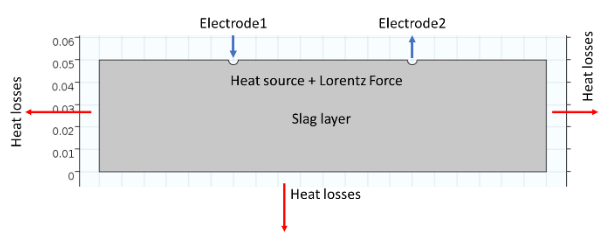


Figure 7. Boundaries and sources of a slag cross section within a slag-cleaning furnace

The solidification creates a source term $\vec{S}$ within the Navier-Stokes fluid flow equations (Figure 6), as described by the Scheil equation (Marin, 2006). The process of slag solidification is nontrivial, however, as slags are non-ideal thermodynamic solutions, and the thermodynamic path depends on both temperature and composition; this requires the dynamic coupling of heat and mass transport with and equilibrium thermodynamics (Marin 2015a, 2015b, 2016). The fraction of solid and liquid fractions are computed through Gibbs Free Energy minimization (Lee, 1999).

For demonstrative purposes, the multiphysics model of Figure 6 has been applied to the 2D domain of Figure 7, in which the wall domains have been excluded for simplicity; the side and bottom boundaries are taken to have convective heat transfer flow. Figures 8, 9 and 10 illustrate the velocity, temperature and phase (fraction of solid or liquid). Figure 8 shows that the Lorentz force does indeed drive the slag away from the electrode zone. This convective flow causes the slag to disperse heat throughout the slag domain. Although slag is a poor thermal conductor, it is known from industrial experience that the temperature gradients inside the liquid slag layer are comparatively low, which is confirmed by Figure 9. Nonetheless, the cooling effect of the side and bottom walls causes the slag to freeze (the solidus temperature of slag is indicated in the figure at 1180°C). The temperature gradient is more pronounced within the solid slag layer, given the effect of heat conduction. Interestingly, Figure 8 depicts the velocity vectors are zero where the slag is fully solid (no movement); indeed, the solid fraction model modifies the behaviour of these equations to simulate solid, liquid or a mixture (Figure 10); this effect is quantified by the Scheil source term within the Navier-Stokes equations.

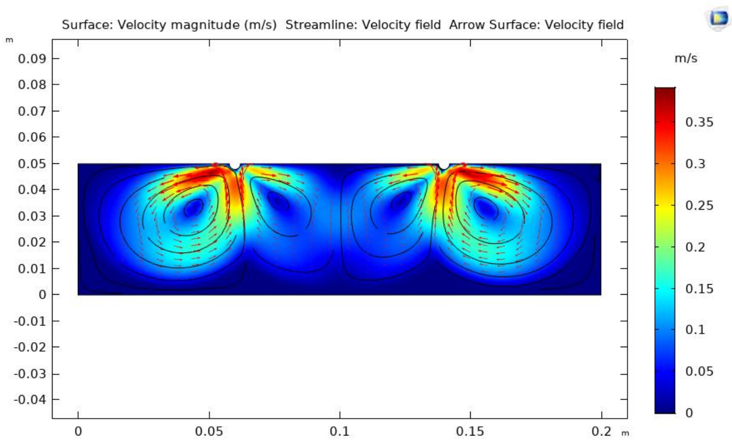


Figure 8. Computed velocity fields within a slag cross section within a simplified slag-cleaning furnace

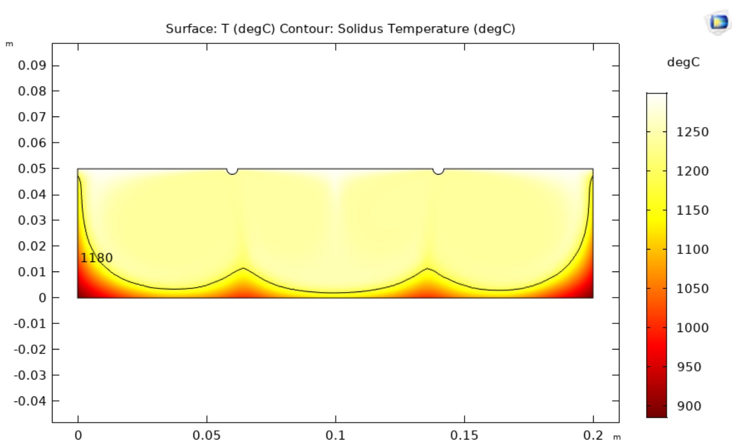


Figure 9. Computed temperature and slag solidification profile within a slag-cleaning furnace

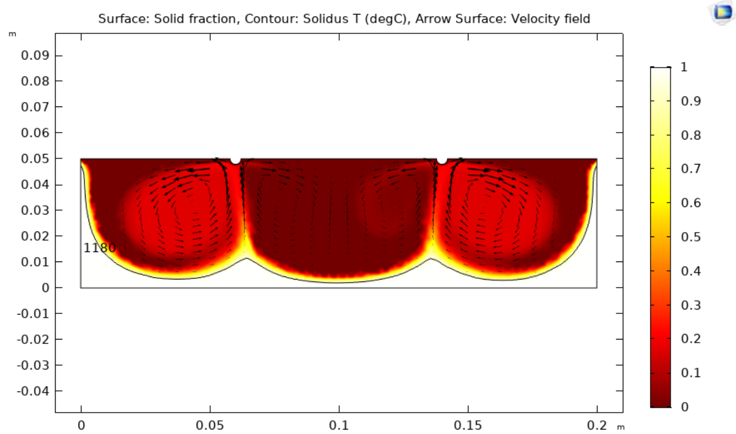


Figure 10. Computed percent solids within a simplified slag-cleaning furnace

The computations illustrated by Figures 6–10 can be repeated with a series of different boundary conditions, representing alternate wall cooling scenarios and slag chemistries. The results of these computations can be a prelude to laboratory and plant trials; in turn, the experimental results can be used to enhance the computations, and refine the design decisions affecting operational modes. Moreover, the multiphysics models can continue to have value for continuous improvement projects, to predict the impact of non-standard operational conditions on the stability of the protective solid layer, thereby prolonging the life of the refractory liner.

CONCLUSIONS AND FUTURE WORK

Continuous improvement projects ensure that consistent mass balancing data is collected (Ferrer et al., 2018), which supports the ongoing refinement of simulation frameworks, such as a DES-TAFD hybrid and multiphysics models; these frameworks integrate thermochemical complexity into operational dynamics, with increasing levels of precision as operational data is accumulated. In turn, the frameworks can facilitate the testing and eventual implementation of improved operational modes. Moreover, these frameworks are a starting point for major reengineering projects that can ensure the sustainability of a smelter (Parameswaran et al., 2018). Indeed, without the availability of such frameworks, it may be difficult to justify large-scale investments into an existing smelter, especially if the smelter is perceived to be acceptable over the short-term.

Even relatively minor investments can be difficult to justify, such as the installation of modern sensors Arias et al. (2018). To evaluate the benefit of a sensor within the converting furnaces, for example, it is necessary to capture how the adjacent equipment (oxygen supply, offgas handing, slag-cleaning, etc.) is currently being operated, and then to simulate the improved operation that would utilizes the hypothetical sensor. The quantitative frameworks developed during CI projects can assist in initial scoping studies (FEL1). During prefeasibility studies (FEL2) the frameworks must be sufficiently broad to represent the entire smelter, with sufficient detail devoted to the critical unit operations and phenomena, allowing a fair system-wide comparison between alternate design options. Multiphysics simulations are then developed to further quantify physicochemical phenomena (typically during FEL3), but only for critical aspects of the smelter that can affect the viability of the design. Simulated multiphysics results are integrated into smelter-wide simulations, through the parametrization of operational modes; moreover, the multiphysics results are used to finalize the dimensions of critical equipment.

Advanced control systems is an emerging area of interest for dynamic smelter simulations (Guo, 2003). In particular, DES-TAFD hybrids can incorporate machine learning algorithms, to determine the economic value of these algorithms, and to assist in their development (Ferrer et al., 2018). Previous work has featured the incorporation of scheduling algorithms into dynamics frameworks to simulate hundred of days (Navarra, 2016); similarly, DES-TAFD frameworks will be able to simulate automated learning processes, as they are fed with historical operating data. It is strongly recommended that advanced control systems be developed through a multiphase approach, beginning with low-cost mass balancing exercises and dynamic simulations, and progresses toward increasingly sophisticated simulations. The modernization of a smelter control system includes the installation of new sensors (Arias et al., 2018), and the development of new modes of operation (Navarra et al., 2019). The multiphase approach builds consensus and determines which features should be incorporated into the control system; by necessity, the approach depends on the experience smelter personnel, including the CI team.

Mature smelters have an important advantage over newly constructed smelters: the continually accumulating experience of operators, engineers and other staff members. Conversely, new smelters are constructed with modern equipment and are better positioned for the foreseeable mineral feeds and environmental legislations. Thus, for existing smelters to be competitive, they can apply their accumulated experience in the formulation of multiphase reengineering projects, resulting in the well-informed implementation of equipment and operating practices.

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