Study on Predicting Electrolyte Temperature of Aluminium Smelting Cells for Power Modulation

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Abstract

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The temperature and superheat of the electrolyte in the Hall-Héroult process play important role in achieving high energy and current efficiency. They provide the thermal energy to preheat materials, to allow phase changes of feeds and final product, and to complete the thermodynamic requirements (overall enthalpy of reaction). With the growing use of renewable energy sources that require frequent power modulation cycles, the monitoring and control of electrolyte temperature and superheat in real-time is becoming pivotal as power input is varied. However, this has been challenging because conventional thermocouples, and their protective sheaths, are rapidly corroded by the electrolyte and thus are unreliable for continuous operation. This paper reports the positive outcome for the continuous model-predictive monitoring of electrolyte temperature, even under power modulation conditions, by embedding thermocouples in the pot lining and on the pot shell for thermal balance calculations. This paper contributes to the monitoring of aluminium smelting cells, especially under variable power conditions, and provides valuable information for optimising cell operations and developing automatic process control systems.

Keywords: Bath temperature monitoring, Power modulation, Real-time monitoring, Model-based soft sensor, Aluminium reduction.

1. Introduction

Controlling both the operating temperature and the electrolyte composition within narrow bands is crucial for achieving high energy efficiency and long cell life of aluminium smelting cells. The electrolyte temperature and its superheat (the difference between bath and liquidus temperature) play important roles in achieving high current efficiencies through limiting the solubility of metal, in maintaining a protective frozen cryolitic ledge on the sidewall refractory, and in limiting the sidewall heat losses and thus the required energy for the process. The coupled variable, superheat, also needs to be always controlled within a narrow band because of the important role it plays in dissolving the batches of alumina that are added at a regular interval.

The process control tasks have always been challenging due to difficulties in process monitoring. Sensors, such as conventional thermocouples and their protective sheaths, are unreliable for continuous operation because of their rapid corrosion by the electrolyte. However, proper process monitoring and control is achieving greater importance in the "renewable energy era" with intermittent energy supply sources requiring frequent power modulation, where cells must operate with varying power input to balance their loads on the power supply grid.

This paper reports the positive outcome for overcoming the challenge for continuous monitoring of electrolyte temperature under such circumstances, by embedding thermocouples in the pot lining and on the pot shell for thermal balance calculations. This methodology will be more reliable than data-based (artificial intelligence) or empirical model-based approaches [1-5], given the lack of high-quality power modulation data with good operation. The long-term aims are to ascertain whether such an approach opens the doors for better thermal control of operating cells when subject to power modulation, and to subsequently develop appropriate cell models and control strategies, including the monitoring and control of cell superheat.

2. Power Modulation

Early power modulation of aluminium smelting cells was considered for multiple reasons, such as mitigating high energy costs or addressing power supply deficiencies [6-9]. In many instances, operational difficulties and process control challenges were reported, including excessive cooling and ledge/freeze build-up [9-12]. Over recent decades, power modulation has regained importance due to the increasing use of intermittent renewables in our energy mix. Due to aluminium smelters being large energy users, they are commonly contractually obligated to provide demand-side response for power grid balancing, thus it becomes impractical to operate the cells continuously at fixed line current.

Renewable sources typically exhibit a diurnal cycle pattern, leading to power modulation schemes in which the power input is also cycled daily [13]. With such a frequency, it is impractical to balance the mass and heat transfers perfectly always. For example, the anode cover thickness of all cells in a potline cannot be altered twice daily to maintain heat loss when power, and consequently heat generation, are varied. Therefore, the control goal may shift, from maintaining a fixed range for electrolyte temperature and composition, to allowing these ranges to fluctuate with line current.

For example, as line current is varied, there is a limit on the amount of heat compensation achievable by adjusting cell voltage through anode-cathode distance (ACD). A low ACD value results in efficiency losses due to increased back reaction caused by the proximity of anodic gases and cathodic metal [12]. Conversely, a high ACD value could pull the anodes out of the electrolyte. For a modern cell technology considered in this paper, with a typical anode immersion depth of 15 cm, the anodes can only be elevated by a maximum of 1.3 cm. This is because electrolyte height is sensitive to anode immersion depth, as modern cells have high anodes-to-electrolyte volume ratio. Additionally, substantial anode beam movement can lead to crust breakage and materials falling into the electrolyte [14]. Other smelters have explored forced air cooling [15, 16] and shell heat exchanger [17] to increase heat removal rate during line current increase [18-22], but its impact on electrolyte temperature will be slow due to the large time constant introduced by the refractory insulators in the cell walls. This implies that under greater magnitudes of power modulation, the electrolyte temperature is expected to shift to a different range, hence it is increasingly crucial to continuously monitor and control it so it remains within acceptable bounds.

Similarly, under power modulation schemes, it is not necessary to control the concentration of alumina and other materials to the same level. Although the base-feeding rate of alumina must adapt to the line current because the current drives the rate of electrochemical reactions, the alumina concentration level can vary. For example, at a larger line current, the alumina

The model is stable if and only if the coefficient of the state is negative [31]. It is evident that this is true, since the control volume properties (m_{B}, c_{B}) and thermal resistances ($R_{\mathrm{B-gas}}$, $R_{\mathrm{B-lining}}$, $R_{\mathrm{B-shell}}$) are always positive. Therefore, the prediction error due to the arbitrary choice of initial condition will be rejected over time.

6. Conclusions

The monitoring and control of electrolyte temperature and its superheat are important to ensure high current efficiencies, to maintain desired ledge profile, and to limit heat losses. This study shows that a dynamic model can predict the bulk electrolyte temperature, even under power modulation conditions. This improves observability of the process, especially under non-standard operating conditions where power input is varied.

Measurements from thermocouples embedded in the pot lining and mounted on the shell of commercial cells were treated as boundary conditions for estimating bottom and side heat losses. By also calculating the process energy and the energy dissipated at the electrode interface and the electrolyte, it is possible to conduct a thermal balance around the electrolyte and metal region. The electrolyte temperature trends predicted by the model also reflects the fast dynamics of anode beam movements and alumina feeding cycles, which are not directly observable from the pot lining and shell temperature measurements. This paper has demonstrated that while pot lining and shell temperatures cannot directly indicate electrolyte temperature, they have potential in model-based approaches for thermal balance computations. Other model inputs required for this approach are line current, cell voltage, and alumina feeding control actions — all of which are readily available measurements/data.

While these findings are encouraging, more robust methods can be developed for real-time soft sensor implementations. For example, it can be automatically calibrated as new daily temperature measurements are conducted. Future work also includes expanding this paper to monitor the spatial electrolyte temperature and superheat, similar to the discretisation level achieved in other works [29, 30, 32-34]. This also requires freeze dynamics to be included, which will couple the mass and thermal balance via phase changes of the ledge. This is becoming important as larger cells are being built and operated at higher amperages. This will provide valuable spatial process information for optimising cell operations and developing automatic process control systems, leading to improved energy efficiency and lowered operational costs under power modulation schemes. More technical and economic analysis should also be conducted to optimise the quantity and the placement of thermocouples to increase sensor life and reduce capital cost.

7. References

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