Model Predictive Control of Maintaining the Superheat of an Aluminium Smelting Cell during Power Modulation

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Abstract

Superheat is a crucial indicator of the thermal balance in the aluminium smelting process. Maintaining the superheat within a narrow range ensures the productivity and energy efficiency. Large fluctuations in superheat can result in undesirable effects such as increased back reactions, sludge formation and reduced current efficiency. Furthermore, during power modulation, the variable power input will affect cell thermal balance and increase the difficulty of cell operations. To reduce the variation of the superheat during power modulation, this paper develops a Model Predictive Control (MPC) approach to maintaining the superheat by manipulating the alumina feed and anode-cathode distance based on real-time temperature measurements or estimation. Through mathematical modelling and simulations, the mass and heat balance inside the cell is regulated during power modulation. This method provides an insight into superheat management for idle operation and power modulation.

Keywords: Aluminium electrolysis, Process control, Model predictive control.

1. Introduction

Controlling the aluminium smelting process is challenging due to its nonlinear characteristics, and coupled mass and thermal balance. Research in the literature mainly focuses on either the control of alumina concentration or the bath temperature and excess AlF_3 concentration [1-4]. Drengstig [2] mentioned the basic framework to control the bath temperature and excess AlF_3, and Kolås et. al. [3] adopted a PI control to control the bath temperature and excess AlF_3 by adjusting AlF_3 feed and ACD, whereas Shi [4] improved the alumina feeding control and used a state observer to estimate the alumina concentration. However, to control the process effectively, both mass balance and thermal balance should be managed simultaneously due to their coupling nature.

The superheat of an aluminium smelting cell is an important variable which can reflect the cell operation status. It is given by the difference between the bath temperature and the liquidus temperature. Controlling the superheat within a certain range is helpful for maintaining stable process conditions. If the superheat increases by 10 ºC, the current efficiency will decrease by 1.2–1.5 % [5, 6]. Superheat is commonly regarded as the thermal driving force in the cell. As it provides the energy to dissolve alumina feed in the bath, a low superheat makes it difficult for alumina to dissolve [7]. On the other hand, increasing the superheat can lead to ledge melting, while decreasing the superheat can cause ledge freezing, both of which can affect the chemical composition of the bath. The liquidus temperature is related to the bath composition, primarily the alumina concentration and the aluminium fluoride concentration, as their concentrations typically change more rapidly over time than others. Kolås [3] used a PID controller with anti-windup to calculate aluminium fluoride feed with assuming the aluminium fluoride consumption can be estimated. Drengstig [8] adopted an almost constant AlF_3 input to control the aluminium fluoride concentration. This input was determined through a simple mass balance calculation to ensure that the average addition matched the average consumption. However, controlling the aluminium fluoride concentration is still challenging as it is relatively easy to add but difficult to remove from the cell quickly. If an excessive amount of aluminium fluoride feed is introduced, it can have a long-term negative effect on the cell process. This may cause a significant decrease in the liquidus temperature, resulting in an increase of superheat and increasing the risk of the ledge completely melting. Regarding the alumina concentration, controlling the alumina feed is more convenient than controlling the aluminium fluoride feed since alumina is the primary material consumed in the production of aluminium. Additionally, an increase of 1 % alumina concentration can lead to a decrease in the liquidus temperature of approximately 5 °C [9]. Therefore, achieving effective control of the superheat requires proper management of both the bath temperature and the alumina concentration.

On the other hand, maintaining the superheat by simultaneously managing the bath temperature and alumina concentration plays a crucial role in power modulation. When the line current undergoes changes, rapid adjustment of both thermal balance and mass balance is necessary. Otherwise, failing to do so can lead to excessive superheat, increasing the risk of complete ledge melting, or insufficient superheat, causing excessive freezing of cryolite. In reference [10], the thermal response of power modulation events was demonstrated using a "lump parameter+" model. Eisma et. Al. [11] presented the cell performance of a TRIMET EPT-14 cell during a 24-hour period of a 20 kA reduction line (from 167 kA to 147 kA), and outlined the corresponding challenges during this process. In order to address the challenge of maintaining a stable process during power modulation, advanced algorithms should be considered. Model predictive control is an algorithm that can provide a powerful framework for controlling dynamic systems. By incorporating model-based predictions, optimization, and real-time decision-making while considering system constraints, MPC can effectively achieve desired objectives. Therefore, to address this challenge and maintain a stable process during power modulation, this paper adopts the MPC method.

The scope of this paper is to introduce a control scheme that maintains the superheat within a narrow range during power modulation in an aluminium smelting process by using MPC. Section 2 provides a concise system description and modelling of the aluminium smelting process. Section 3 outlines the controller design for MPC, while section 4 presents the simulation results.

2. System Description

The Hall-Héroult process is the only industrial method for producing aluminium. In this process, alumina is dissolved in molten cryolite at high temperature. When current is passed through the bath, aluminium ions migrate to the cathode, where they are reduced to form aluminium metal. Simultaneously, carbon dioxide or carbon monoxide is generated and released at the anode. The fundamental structure of an aluminium smelting cell is depicted in Figure 1. The overall electrochemical reaction, including reduction of alumina (forward reaction) and reoxidation of aluminium in the electrolyte is:

$$2\eta Al_2O_3 + 3C = 4\eta Al + 3(2\eta-1)CO_2 + 6(1-\eta)CO \quad (1)$$

where: η Fractional current efficiency, typically = 0.92-0.96.

5. Conclusions

Superheat plays a critical role in the aluminium smelting process as it impacts energy consumption and cell lifespan. Maintaining stable superheat is vital for efficient operation. In this paper, the MPC method is employed to maintain a stable superheat by manipulating the alumina feed and ACD, driving the process variables of alumina concentration and bath temperature towards their reference values. By optimizing these variables while considering constraints with MPC, the paper demonstrates stable superheat performance during power modulation. This research lays a foundation for enhancing process performance during power modulation. In future research studies, it would be beneficial to improve the accuracy of the model and explore more advanced control strategies to overcome limitations and further advance the application of MPC.

6. References

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