Preliminary Development of a Transient 1D-Electrical Model of Hall-Héroult Electrolysis Cells

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Abstract

Alumina is transformed into aluminium through electrolysis in the Hall-Héroult process. An efficient production of primary aluminium requires precise control and optimization of electrolysis cell operations. However, the process is inherently complex, involving intricate interactions between physical and electrochemical phenomena. Key factors such as magnetohydrodynamic effects, uneven electric current distribution, variability in anode-cathode distance (ACD), changes in the anode structure, and bubble formation all contribute to the difficulty in achieving real-time monitoring and management of critical parameters. These challenges hinder the ability to predict and control the electrolysis process effectively. To overcome these hurdles, this study introduces a transient 1D-electrical model that analyses the temporal evolution of various parameters in the electrolysis cell. The model incorporates simplified physical laws, which provide valuable insights into the dynamic nature of the system. By analysing the temporal behaviour of key parameters, the model offers predictions on the operation of the cell, enabling more accurate monitoring of the anode and cathode performance. These insights facilitate improved management of anode consumption, better distribution of current, and the optimization of operational conditions, ultimately leading to enhanced Hall-Héroult process efficiency. This approach holds promise for advancing the production of primary aluminium by addressing critical challenges and optimizing the overall electrolysis process.

Keywords: Hall-Héroult process, Aluminium reduction, Electrical resistances, Anodes.

1. Introduction

Aluminium is an essential material in numerous industries thanks to its lightweight nature, excellent strength-to-weight ratio, and strong resistance to corrosion [1]. Aluminium is produced in several steps, beginning with the extraction of bauxite ore, followed by refining it into alumina (Al_2O_3) using the Bayer process [2]. The alumina is then reduced to pure aluminium metal through the Hall-Héroult process, an electrolytic method in which alumina is dissolved in molten cryolite, and electric current is passed through the solution to separate aluminium at the cathode and oxygen at the anode [2].

Achieving efficient and stable operation of Hall-Héroult electrolysis cells requires precise control of key parameters such as electric current distribution. However, in practice, these parameters fluctuate due to the complex interplay of electrochemical, thermal, hydrodynamic, and magnetohydrodynamic effects. Key challenges include, among others, uneven current distribution, dynamic variations in anode shape due to consumption, changes in anode-cathode distance (ACD), and gas bubble formation. These factors can lead to alumina dissolution inefficiencies, anode effects, anode incidents, disruptions in magnetohydrodynamic stability, and potential short circuits, all of which compromise process efficiency [3].

To effectively investigate the operation of electrolysis cells, several studies have been conducted, including models of anodic current distribution [3] and alumina distribution behaviour [4]. Several of these models require significant computational time, which makes them unsuitable for real-time control. Having an accurate model for real-time monitoring and predictive analysis of the electrolysis cells is essential.

Therefore, to address the limitations of previous models and provide a more precise representation, this study develops a transient one-dimensional (1D) electrical model that captures the temporal evolution of key electrolysis parameters. Using more accurate relationships and alternative methods to calculate the resistance of various parts of the electrolysis cell enhances the richness and reliability of this model. Therefore, this approach offers valuable insights that support improved process control, and enhanced overall efficiency in primary aluminium production.

2. Methodology

This study introduces a one-dimensional (1D) transient electrical model to simulate the behaviour of a Hall-Héroult electrolysis cell over time. Each cell has 40 prebaked anodes that are connected in the model to the electrolyte bath, the cathode, and various structural components, enabling continuous current flow and aluminium production. The modelling approach relies on an equivalent electrical circuit formed by a combination of resistances in series and in parallel. The resistance values vary over time as a function of physical parameters, including anode height, metal pad height fluctuation, material properties, and other influencing factors.

To accurately capture the time-dependent resistance of the anode, COMSOL Multiphysics is employed to model its complex geometry and pre-calculate its resistance at various heights, accounting for its gradual consumption throughout the operational cycle. These simulation results are then integrated into a Python-based computational framework, where the time-varying anode resistances are used to update the overall electrical network. This integration enables the calculation of the equivalent resistance of the cell at each time step and provides a transient view of the current distribution and electrolyte behaviour. The following section provides a detailed explanation of the electrical modelling of the electrolysis cell.

2.1 Electrical Modelling of the Electrolysis Cell

According to Figure 1, the electrolytic cell is modelled as a parallel network of 40 resistors, each representing a complete electrical path that includes one anode along with other connected components. This configuration reflects the irregularity of electric current distribution, with each electrical path carrying a different current due to the varying resistance associated with its physical state.

Each electrical path is modelled as a local sub-network of series and parallel resistors, representing its internal components such as the rod, carbon anode, bath, cathode, and collector bar (Figure 2). The resistance values are dynamically updated over time based on the evolution of physical parameters, such as anode height, material properties, and ACD. This detailed structure allows the model to accurately capture local electrical behaviour.

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7. References

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