Modelling of the Preheating Section in Anode Baking Furnaces - A CFD Approach and a Mass-Energy Conservation Method

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Abstract

Among the various stages in anode production, the baking process stands out as the most energy-intensive, cost-demanding, and quality-defining phase. Despite its significance, one critical section of the process, i.e., the preheating section, remains challenging to analyse, primarily due to its inherent complexities, such as the release of volatiles from the anodes and their subsequent combustion in the flue channel. This knowledge gap has persisted for decades, largely due to the lack of advanced modelling approaches tailored to the unique challenges of the preheating section. In this study, we introduce a Computational Fluid Dynamics (CFD) model of the preheating section in anode baking furnaces. This model provides insight into the intricate interactions of volatile release, heat transfer, and combustion phenomena. Complementing this, we introduce a simplified model based on mass and energy conservation principles, and accounting for the effects of tie-bricks within the flue channel, a critical aspect often overlooked by previous studies. Our findings reveal a good accuracy of the proposed models, with an average temperature prediction discrepancy of 5 °C between the CFD and the simplified model based on mass-energy conservation. Moreover, while the CFD simulation requires approximately three hours of computational time per furnace section, the simplified model achieves equivalent precision in just three seconds, offering an unprecedented combination of speed and reliability.

Keywords: Anode baking furnace, Preheating section, CFD simulation, Mass-energy conservation, Volatile release and combustion.

1. Introduction

Aluminium, valued for its low density, high strength-to-weight ratio, and excellent corrosion resistance, is vital across many industries [1]. Its production begins with bauxite, refined into alumina through the Bayer process [2]. The Hall–Héroult electrolytic process then transforms alumina into pure aluminium by dissolving it in molten cryolite and applying an electric current [2]. This deposits aluminium at the cathode while oxygen reacts with carbon anodes to produce carbon dioxide [3, 4]. Because the carbon anodes are consumed in this reaction, a continuous supply of high-quality anodes is critical for uninterrupted aluminium production.

Creating carbon anodes involves several key stages [5]. Initially, petroleum coke, coal tar pitch, and recycled anode materials are blended to form a uniform mix. This mix is then compacted into shape, often using vibro-compaction or molding techniques, resulting in green anodes. These green anodes undergo a baking process in specialized furnaces to enhance their structural, chemical, and thermal properties. Baking is essential as it increases the density and electrical conductivity of the anodes while reducing their reactivity with air. Once baked, the anodes go through the rodding phase, where they are equipped with attachments that allow them to be connected to the electrical circuit in the electrolytic cell.

The baking stage in anode production stands out as especially important due to its high energy consumption and its strong influence on the final quality of the anodes. Due to the complexity of the baking process, computational modelling, particularly using Computational Fluid Dynamics (CFD), is widely used to analyse and optimize furnace operations. In this regard, some investigations have focused on selecting the most suitable numerical models to simulate the key physical phenomena in the furnace. For example, the PDF (Probability Density Function) model is often recommended for combustion processes in heating section, the realizable k-ε model for turbulence, and the Discrete Ordinates Method (DOM) for radiative heat transfer [7]. Grégoire and Gosselin [6] performed a comparative study of three combustion models, Eddy-Dissipation, PDF, and a simplified combustion approach, highlighting how radiation significantly affects temperature profiles, while species diffusion influences flame behaviour slightly, and buoyancy plays a minor role in the firing section. Other studies have explored how to improve furnace efficiency and reduce energy use. Changes to the flue-wall geometry have led to better heat retention and more uniform baking of anodes. Designs that eliminate internal baffles have been shown to promote more even temperature distribution [8].

While CFD delivers detailed results, simplified models based on mass and energy balances offer a more practical and efficient alternative, for example for control purposes, enabling analysis of the entire furnace with significantly less computation time. Bui et al. [9] developed a one-dimensional model that includes both the flue and pit along the flow direction, though it does not account for flow redirection caused by internal baffles. Zhang et al. [10] later improved the model by representing the pit in two dimensions while keeping the flue channel one-dimensional. Further refinement was made in a subsequent study [11], where the flue channel was modelled in two dimensions to capture the effects of baffles, and the pit was simulated in a pseudo-3D format.

Based on the literature review, all CFD-based studies have concentrated on the heating section, with no research yet addressing the performance of the preheating section. Moreover, the existing simplified models are limited to cases without tie-bricks in the flue channel, making them less reliable for representing real furnaces used in smelters, where tie-bricks are commonly present. To address the gaps in previous studies, this work presents a CFD model of the preheating section of the anode baking furnace, along with an improved simplified model based on mass and energy conservation. The proposed simplified model accounts for the presence of tie-bricks in the flue channel, making it more representative of actual furnace configurations. Both models are then compared in terms of accuracy and computational cost.

2. System Overview

The anode baking process is carried out in an anode baking furnace, which consists of several connected sections with pits filled with green anodes and packed coke. A schematic of the anode baking furnace is depicted in Figure 1. The process is divided into three main zones: preheating, heating, and cooling, each playing a key role in determining the final anode quality. In the preheating zone, green anodes are gradually heated from room temperature to approximately 700–750 °C over a period of three to five days [6]. The slow temperature rise is essential to avoid internal cracks or structural failure. During this stage, volatile compounds from the pitch binder evaporate and diffuse through the porous anode and coke bed. These volatiles burn in the flue channels, providing about 40–50 % of the total furnace energy. To ensure safe and uniform heating, the rate is limited to around 15 °C per hour [11]. Once the anodes are preheated, they enter the heating zone, where the temperature is further raised to around 1 100 °C [6]. This is achieved using burners that supply the remaining 50–60 % of the total furnace energy. In this zone, carbonization of the pitch is completed, and the anodes reach their final baked structure. Proper temperature control in this phase is crucial to ensure uniform carbon quality and minimize defects. In the cooling zone, baked anodes gradually cool down to below 300 °C before being removed from the furnace [6]. Heat from the hot anodes is recovered and used to preheat evaluated and compared in terms of accuracy and computational efficiency. The key contributions of this research are as follows:

- Our findings show a maximum temperature prediction discrepancy of just 1.5 % between the CFD model and the modified simplified model based on mass-energy conservation.
- Furthermore, while the CFD simulation requires approximately three hours of computational time per furnace section, the simplified model achieves equivalent precision in just three seconds, significantly reducing both computational time and associated financial costs, offering an unprecedented combination of speed, reliability, and affordability.

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8. References

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