A CFD Study of Bubble Dynamics and Voltage Drop in Slotted Anodes

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Abstract

This paper extends our previous research (ICSOBA, 2023) by introducing the variation of bubble voltage drop during the slotted anode life span (~24 days) into the existing Computational Fluid Dynamics (CFD) model. This enhanced model investigates the gas dynamics and bubble voltage drop in an aluminium electrolysis cell. Numerical simulations for two anode slots inclinations (20 mm and 80 mm) were performed using COMSOL Multiphysics software based on the finite element method. The CFD model couples turbulent flow, phase transport, and secondary current distribution physics. The latter gives the voltage drop caused by the gas concentration and its layer thickness underneath the anode, while Navier-Stokes equations and phase transport physics give the velocity and pressure profiles as well as the gas volume fraction distribution, respectively. The standard k-ε turbulence model was used. The results reveal how different parameters vary throughout anode life span like the gas bubble voltage drop, bath mixing efficiency caused by pushing the gases towards the central channel, and heat transfer through the side wall due to the change in flow stirring, corresponding to the variation of gas amount passing to the side channel. These findings can help the optimization of slotted anode designs in industrial cells.

Keywords: Aluminium electrolysis cell, Slotted carbon anode block, CFD, Bubble-induced turbulence.

1. Introduction

During primary aluminium production, gases are generated by electrolysis underneath anodes at high temperature of about 960 °C. While these gases (typically carbon dioxide, CO_2) aid alumina dissolution and improve heat transfer within the cell, the turbulence they provoke increases bath hydrodynamics instability and their electrical insulating properties decrease the effective area for electric current flow, leading to a higher voltage requirement (voltage drop) [1-3]. This gas bubble voltage drop can be responsible for as much as 10 % of energy loss through Ohmic heating in aluminium reduction cells [4]. To minimize this energy penalty, aluminium smelters employ various strategies, one of which involves anode slots. These slots, as referenced in different experimental works and industrial trials conducted to record the impact of anode shape on the hydrodynamics and potential fluctuations [5-11], can significantly reduce the anode voltage drop and the whole pot noise compared with traditional anodes without slots. To clearly observe the released gas behaviour and evaluate its impacts on the bath hydrodynamics, while avoiding the harsh operational conditions in an electrolysis cell (high temperature, high corrosive media, and high electromagnetic field), engineers and researchers used lab-scale models using alternative liquid-gas systems instead of electrolytic CO_2 gas, based on the idea that the dynamic viscosity of some liquids at 25 °C is almost the same as that of the cryolite at 960 °C [12-16]. The researchers found that slotted anodes significantly increased the rate of bubble removal by providing a direct pathway for bubbles to rise to the surface.

The cited studies, along with others, highlight the complexity of experimentally studying bath hydrodynamics coupled with bubble voltage drop, particularly with slotted anodes, due to multiple factors. Consequently, existing experimental research often employs idealized configurations – perfectly horizontal anodes with square edges and sidewalls – which may not directly translate to real-world industrial cells. To cover these missed elements, numerical models have been developed allowing better understanding of this topic. In parallel to his experimental work using molten bath of copper sulphate ($CuSO_4$) as aqueous electrolysis solution, Sun et al. [17] have also proposed a 3D transient mathematical model that combines discrete phase model (DPM), discrete-continuum transition model (DCTM), and volume of fluid (VOF) method to track the dispersed bubble trajectory, bridge the dispersed bubble to continuous gas, and resolve the deformed bubble surface, respectively. They have shown that slots decrease the bubble diameters and reduce the residence time by shortening the bubble motion distance. They have illustrated as well that increasing electric current provokes, on one hand, an acceleration in bubble coalescence and, on the other hand, a decrease in their collision probability. In their previous work, Sun et al. [18], coupled magnetohydrodynamics and VOF model to deeply investigate the impact of slotted anodes on bubble behaviour through a 3D transient model. They demonstrated that using slotted anodes provokes an increase in the time-averaged gas bubble removal rate from 36 % to 63 % and a decrease in the bubble layer thickness by about 3.5 mm (17.4 %). Poncsák et al. [19] proposed a bubble layer simulator that models the impact of gas bubbles on voltage fluctuations in aluminium electrolysis. Their simulations revealed that well-placed slots in the anodes significantly reduce both the voltage fluctuation range and the average voltage, especially for new anodes without edge rounding. A CFD study by Zhu et al. [20] investigated the impact of slotted anodes on bath flow and alumina transport in aluminium reduction cells. Their findings indicate that slotted anodes increase the maximum flow velocity but slightly decrease the average horizontal velocity. This results in a more uniform distribution of alumina compared to unslotted anodes. Gusberti and Severo [21] investigated the impact of bubble growth, coalescence, and detachment from the bottom of anodes on the variation of bubble voltage drop. They proposed a numerical model that couples electric equations with the multiphase bath/bubble flow where the presence of gaseous phase resistance results in local current density perturbations. Their work [21] revealed a high sensitivity of bubble behavior and gas layer voltage drop to the anode geometry, inclination, as well as the slot type and number.

In our previous paper [22], a numerical model based on turbulent flow, coupled with phase transport physics was proposed with the intention of thoroughly investigating the role of slotted anodes on the evacuation of the gas phase generated at its bottom surface, the mixing in the central channel, and heat transfer in the side channel. This was obtained by evaluating the bath hydrodynamics as well as the gas phase redistribution through different channels after its generation underneath the anode, taking into account anode rounding, measured on a cut-out cell, that is produced by the concentration of the electric current at anode edges. It was shown that the more the slot is inclined towards the central channel, the higher the gas amount passing through the central channel and the less to the side channel. This decreases bath stirring in the side channel which helps the ledge stability. It was demonstrated as well that greater width of the slot helps better gas removal from the bottom of the anode, which can lead to a decrease in the gas concentration underneath.

The present paper builds upon our ICSOBA 2023 work [22] by incorporating the dynamic change in bubble voltage drop over a typical slotted anode lifespan (~72 shifts, 24 days) into our existing CFD model. This upgraded model provides a better understanding of gas behaviour and voltage drop in an aluminium electrolysis cell. The paper is structured as followed: Starting with a description of the mathematical model in the second section, the model validations with experimental data from the literature, and various configurations to be studied are then described in the first part of Section 3. Subsequently, the second part (Section 3) is devoted to discussion and analysis of different simulated cases.

anode lifespan (~24 days, 72 shifts) by coupling the existing CFD model with the secondary current distribution equation that accounts for both anode reaction kinetics and ohmic losses in the electrolyte. Our results show that the variation of the gas concentration underneath the anode and the generated bubble voltage drop over the anode life follow principally three stages depending on the slot consumption and immersion level. The first stage represents an open slot with low gas concentration and a corresponding lower bubble voltage drop. In contrast, the final stage of fully consumed slots has high gas concentration and the highest bubble voltage drop. The intermediate stage is characterized by an increase in gas concentration **as the slot becomes increasingly immersed, trapping more gas beneath the anode.** This rise in gas concentration leads to a higher bubble voltage drop.

Time-average bubble voltage drop throughout the anode lifespan for higher slot inclination (80 mm) is higher than for 20 mm slot inclination. However, higher slot inclination gives lower average bubble voltage than smaller inclination during the immersion period. This is due to greater number of shifts during which the 80 mm slots remain partially immersed.

Our results also show that the gas distribution through the central and side channels over the anode lifespan depends strongly on the slot inclination and its immersion level. The amount of gas flowing to the central channel is most of the time higher than to the side channel. Higher slot inclination promotes earlier gas flow to the central channel which helps alumina dissolution. Additionally, the peak amount of gas in the side channel is lower with the 80 mm inclination. This suggests that the impact of gas flow on the side ledge is smaller with steeper slots. On the other hand, high slot inclination of 80 mm shows higher time averaged bubble voltage drop (7 mV) than 20 mm inclination; this is a small penalty compared to the benefits of side freeze stability and better alumina dissolution in the central channel.

This model will help optimizing anode slot design in aluminium reduction cells.

5. References

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