An Equation for Bubble-Induced Voltage Drop on Slotted and Non-Slotted Anodes

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Abstract

The standard industrial aluminium electrolysis process relies on consumable carbon anodes, where the carbon is oxidized, generating mostly CO_2 at the anode bottom surface, forming bubbles inside the electrolyte. The presence of the bubbles is undesired because it increases the Anode-to-Cathode Distance (ACD) voltage drop, thus increasing the cell specific energy consumption. These bubbles are removed from anode bottom and discharged at the bath top surface, at the sides and in between anode channels.

Previous Computational Fluid Dynamic (CFD) simulations [1] have demonstrated that the anode geometrical features such as: anode size and inclination, number and size of slots, and edge-rounding radius strongly impact the bubble flow and the resulting ACD voltage drop. Slotted anodes have become the standard design in the industry in this century, because the gas removal from ACD space is more efficient, reducing the voltage drop caused by bubbles. However, it is very difficult to quantitatively determine the impact of slots on ACD voltage drop without numerical modelling; which usually requires prototyping and extensive data measurements and processing. It would therefore be highly beneficial if such estimation could be made using published analytical equations.

This work proposes the development of analytical equations estimating bubble-induced voltage drop for slotted and non-slotted anodes, capable of considering a range of geometrical anode features such as anode length, width, channel height, nominal current density, slot width, slot height and others. The analytical equations are derived from detailed 3D multiphase CFD results where transient bubble structures can be followed along their paths, including growth, coalescence, and detachment from the anode surface. This provides a quick tool for design evaluation by process engineers, without the need for intensive computational power. The present work results are compared with classical literature formulae compilations [2], developed for non-slotted anodes which were standard at that time.

Keywords: Bubble voltage equation, Slotted anode, Anode shape, Bubble-induced voltage drop, Bubble-induced flow.

1. Introduction

Most of the modern aluminium electrolysis cells utilize carbon blocks as consumable anodes, taking advantage of the carbon oxidation contributing to the fulfilment of energy requirements for alumina reduction, and decreasing the electrical energy input compared to inert anodes. These carbon blocks are placed inside the cell, arranged in a horizontal array over the cathode panel and the bath. The electrical current flows through the anode, molten bath ACD, and molten metal into the cathode panel. In such a configuration, the gas (mostly CO_2 and CO) generated beneath the anode bottom surface forms bubbles which travel attached to that surface. Because the gas is an electrical insulator, it disturbs the path of current lines and reduces the local effective area for electrical conduction from anode to bath, covering part of anode surface area. The continuous removal of the gas under the anode surface is a difficult and complex process, and it is important for the decreasing of the bath bulk voltage drop. The bubbles must escape from the ACD space where they are formed and travel towards the anode sides and bath channels where they can be discharged to the cell hood space and then collected by the cell exhaust system. The driving force for such movement is the buoyancy, which is generated from the significant difference in density between gas and bath. In this perspective, the study and understanding of the bubble flow inside the bath is important for improving anode design and configuration to minimize bubble-induced voltage drop which is closely related to the bubble removal efficiency.

The bubbles present a life cycle inside the bath composed of nucleation, growth, coalescence and detachment processes leading to a complex multiphase flow in the ACD space, side and center channels. A numerical model capable of describing this process was presented in an earlier work [1] and the model was also used to calculate the voltage drop induced by bubbles inside the bath. One of the conclusions of the previous modelling work was that the shape of the anode bottom surface significantly affects the voltage drop outcome, and the modelling must consider realistic consumed shapes to obtain meaningful results. The shape can be obtained from measurements of real consumed carbon blocks (as presented in [1]) or from numerical modelling results. A consumed anode usually presents a rounding shape formed during the anode life in the cell due to the concentration of electrical current and the resulting higher wearing rate at sharp edges, therefore equalizing the current density across the entire anode bottom surface. The stabilized anode bottom shape and edge curvature are dependent on anode current density distribution; which in turn is a function of the ohmic, bubbles, chemical decomposition and polarisation voltages.

The use of consumable slotted anodes has become a standard industrial practice since the beginning of this century. The development and deployment of slotted anodes in Alcoa industrial cells have been described by Wang et al. [3]. In their work, the overall gain obtained by the slot implementation in the smelters ranged from 30 mV to 160 mV, depending on the cell technology. In addition, the voltage noise was also reduced when slots are used. The observed voltage gains variation was dependent on anode current density, anode size and shape, as well as slot type and depth. However, no quantitative function of anode slot impact gain regarding each geometrical parameter or current density could be provided in [3].

In this work, the bubble flow model presented in the previous article [1] has been improved with the inclusion of more geometric features and more appropriate boundary conditions. Then, the new model used in this article is employed to explore the impact of geometrical features and the variation of process parameters on the bubble-induced voltage drop: anode length and width, anode bottom slope, ACD, slot thickness, bath height and nominal current density. The slotted anode configuration chosen is the two longitudinal slotted anode, dividing the anode bottom surface in three equal areas. This configuration is commonly seen in the industry and is frequently used in high-amperage modern cells.

The aim of this research is to produce a set of results that can be used to formulate a curve-fitted analytical equation to predict the bubble-induced voltage drop for any anode configuration within a specified validity interval. These intervals are proposed based on realistic ranges observed in the industry. By using this predictive equation, process engineers can quickly estimate the bubble voltage drop component of the cell voltage, with or without slots, for a more accurate and modern description of the cell voltage breakdown contrary to the classical approaches [2, 4], which do not even consider the existence of anode slots; a common industry practice today.

numerical model. The present work greatly improves and modernizes the estimation of bubble-induced voltage drop compared with classical literature [2 and 4], as it now considers additional geometric features and slots which were not present in the previously cited works.

Specifically, the modelling results identified the following trends regarding bubble-induced voltage drop:

- There is an important difference in bubble-induced voltage drop between slotted and non-slotted anodes with the same geometric parameters. This was an expected outcome of the CFD modelling already demonstrated before by modelling [1], and by experimental works [3].
- A strong increase in voltage drop of the bubble layer with current density is observed, not only explained by the bath resistance but also because the gas coverage also increases;
- Bubble voltage drop is not sensitive to ACD because the bubble film is too close to the anode surface. The same can be concluded about the width of the bath channels;
- Bubble voltage drop presents a mild decrease with bath height;
- Slot width has a small impact on voltage drop. The optimal slot width range lies between 10 mm and 15 mm, which is already a common industrial practice;
- Bubble voltage drop increases with anode length because the travel distance and the residence time of the bubbles are also increased;
- In the same manner, bubble-induced voltage drop increases with anode width because the travel distance and the residence time of the bubbles are also increased;
- Anode bottom surface inclination slightly reduces bubble voltage drop comparing to horizontal and very low inclination. However, for typical anode bottom inclinations found in modern cells, this parameter is almost neutral.

In this work, results and findings were obtained considering non-slotted versus two-slotted anodes of longitudinal orientation, where the slots are located dividing the anode bottom in three equal areas. By analysing the bubble layer pattern, it is possible to observe higher bubble coverage fraction in the central part of the anode between the slots. A follow-up study could vary the distance between slots to potentially find the optimal distance.

An experimental study is suggested to test the accuracy of the equations provided in this article. Various tests can be conducted on both laboratory and industrial scales to confirm the findings presented here.

6. References

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