Impact of Slot Inclination and Thickness on the Distribution of Gas Bubbles Generated below the Anode

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Abstract

This paper reports on a numerical study of the impact of the anode slot design on the evacuation and distribution of the electrolysis gases (mainly CO_2) generated at the bottom surface of the carbon anode in an aluminium electrolysis cell. Different slot inclinations (20 mm and 80 mm) and thicknesses (6 mm, 8 mm, 11 mm, and 22 mm) were investigated in this study, using COMSOL Multiphysics software based on the finite element method. The computational fluid dynamics (CFD) model consists of coupling turbulent flow and phase transport physics. The latter solves the phase transport equation and gives the gas volume fraction distribution in the computational domain, while the former gives principally the velocity and pressure profiles by solving the Navier-Stokes equation. The standard k-ε turbulence model is used. This study helps to understand the impact of the slot design on bath mixing in the central channel, affecting alumina dissolution, and side channels, affecting heat transfer to the walls and ledge profile. The outcomes are used to optimise slot designs in industrial cells.

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

1. Introduction

In industry, the production of primary aluminium consists of its reduction from alumina. This process occurs principally in an aluminium reduction cell called Hall- Héroult cell. Using direct electric (DC) current, aluminium oxide (alumina) is reduced in the molten electrolyte under high temperature (about 960 °C). This electrochemical reaction produces ideally aluminium (liquid metal) and oxygen O_2 (gas). The latter reacts with carbon anode and produces carbon dioxide gas (CO_2) bubbles at the bottom surface of the anode. The generation of such a gas phase induces bath circulation which helps, on one hand, dissolving alumina, and on the other hand, it increases heat transfer between the bath and the cell walls [1-3]. However, the existence of the gas bubbles for longer time underneath the anode block leads to their coalescence and forms a more continuous insulating gas layer, which increases electrical resistance in the anode-cathode distance (ACD) manifested as bubble voltage drop. The gas coverage of anode bottom surface increases with decreasing alumina concentration, reaching 80 % coverage when approaching the anode effect. Anode effect occurs at 1-2 % of alumina concentration in the bath; at this concentration another reaction occurs on the anode surface, generating perfluorocarbons (PFCs), which cover the entire anode bottom with a thin insulation layer, which increases cell resistance and cell voltage to typically 15-30 V [4]. To avoid formation of large bubbles many modifications of the anode shape, such as anode slots, have been performed in order to decrease the residence time of bubbles on the bottom surface of the anode block [5].

1.1 Experimental Studies

Several experimental works dealing with this subject are found in the literature. Because of the harsh operational conditions (high temperature, high electromagnetic field, and highly corrosive media), researchers have worked experimentally with other liquid-gas systems instead of cryolite-CO_2 system [6-8]. This approach is valid since the dynamic viscosity of other liquids at 25 °C is almost the same as that of the cryolite at 960 °C. Feng et al. [6], studied hydrodynamics of water under three anodes in presence of air injection to create bubble-induced turbulence). They used the particle image velocimetry (PIV) technique to measure the flow field. The results showed that, on one hand, the presence of slots in the anodes improved the hydrodynamics of the bath. On the other hand, the slots helped to quickly remove the gas from the bottom surface of the anode to the slots by which the gas easily evacuated to side channels. This contributes to increase mixing rates at the central and side channels. Other researchers [9-10] studied the dynamics of bubbles released from the bottom surface of graphite anodes in a molten bath of copper sulfate ($CuSO_4$). The results showed that the presence of a slot in the anode significantly increased the rate of bubble removal. The researchers attributed this to the fact that the slot created a pathway for the bubbles to rise to the surface more quickly.

1.2 Computational Fluid Dynamics (CFD)

With the remarkable development of the computational resources, researchers have focused on the CFD model development to better understand the mechanisms of gas bubble removal from the bottom surface of the anodes. Numerical models based on separated phases have been widely used in the treatment of this subject. Euler-Euler approach has been used by Hreiz et al. [11] to investigate the electro-generation of bubbles from a vertical electrode considering the impact of external forces as well as their coalescence. The generation of bubbles by the electric current applied to the cell was not present in their model because, as cited in the literature [11], it is difficult to ensure the convergence of the magnetohydrodynamic model based on Euler-Euler approach, contrary to Euler-Lagrange approach. The latter has been used by Hreiz et al. [12], where the electro-generation of bubbles function of the current density was considered in the model, that gave good agreement with experimental results obtained in parallel (using PIV). Wang et al. [13] proposed a CFD model based on volume of fluid (VOF) method to investigate the morphology of bubbles generated and released from the bottom surface of the anodes. In their model, researchers [13] neither included the force on the bubbles during their movement nor their coalescence in the bath. They showed that the slots provide the possibility for more gas removal. Sun et al. [14], proposed a 3D transient model that couples magnetohydrodynamics and VOF model to profoundly understand the effect of slotted anodes on bubble behaviour. The results showed that the time-averaged gas bubble removal rate increased from 36 to 63 % when using slotted anodes and the bubble layer thickness is reduced by about 3.5 mm (17.4 %). To go deeply in their study, Sun et al. [14] investigated the transition of bubble sizes and its coalescence from micro-to-macro-scale, coupling the discrete bubble model (DBM) and VOF method. The model results had good agreement with the experimental data existing in the literature [15]. They found principally that bubble release frequency increases with increasing current density. From the different studies cited above and others existing in the literature, researchers concluded that the study of the bath hydrodynamics is likely to be complex and related to multiple parameters, especially for slotted anodes. It is one of the reasons why these different works are reported for idealised configurations since the anodes were perfectly horizontal with square edges as well as a square sidewall geometry, which is not necessarily directly relevant to industrial cells.

In the present paper, a numerical model based on turbulent flow coupled with phase transport physics is proposed with the intention of increasing the understanding of 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 is obtained by evaluating the bath

The results of this study can be used to optimise the design of anode slots in aluminium reduction cells. By understanding the impact of slot inclination and thickness on gas distribution together with the bath mixing in the central channel and heat transfer at the side channel, it is possible to design slots that improve the efficiency of the cell by better alumina dissolution, lowering bubble voltage drop and to reduce the risk of premature cell failure with a better ledge covering of the side walls.

5. References

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