Understanding the Factors Influencing Carbon Dioxide Dilution in an Aluminum Electrolysis Cell

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Abstract

The Hall-Héroult process is widely employed worldwide to produce aluminum. Inherently, this process also generates significant emissions of carbon dioxide, a greenhouse gas as a by-product of the reaction. As the bubbles formed during the electrolysis escape from the electrolysis cells, they induce the generation of a gas flow underneath the anodes, which are expelled due to the buoyancy forces of the melt. The rate of the gas flow generated, and the incident gas concentration of the output gas will be dependent on numerous different factors. In this work, a numerical model was developed to replicate the chemical reactions in the vicinity of an anode assembly leading to the generation of carbon monoxide and carbon dioxide. The output gases are then rooted to the gas exaust with fluctuating concentrations due to changes in the conditions, which may result in variations in the amount of carbon dioxide and carbon monoxide being produced under steady state. Hence, the purpose of the experimental plan is to simulate the operations of a specific number of different situations so as to illustrate the extent of the operational conditions that can be expected in the industry in the future. In order to accomplish this purpose, the numerical model was developed using ANSYS Fluent and a validation process was developed to confirm the accuracy of the model. During the investigations, various conditions were meticulously examined, analyzed and evaluated, including the pressure at the gas exhaust point, the air entering the electrolysis process, the effect of current efficiency, the amount of current flowing through the cell, the height of the channel, the anode size and other factors, in order to comprehensively understand the effect of these factors on the concentration of gas within the cell.

Keywords: Hall-Héroult process, Chemical reactions, ANSYS Fluent, Gas concentration, Current efficiency.

1. Introduction

Aluminum is a metal widely used in a variety of applications, including transportation and construction, due to its unique properties [1]. Canada is one of the major producers and exporters of aluminum. In 2020, Canada produced approximately 3.2 million tonnes of aluminum, with 90 % of this production taking place in Quebec [2]. Various strategies, such as increasing energy and material efficiency and incorporating renewable energy sources, have been implemented to reduce the environmental impact of aluminum production. While progress has been made, there is still a long way to go in achieving sustainable aluminum production. The industry must focus on working towards a low-carbon future that balances environmental concerns with economic growth [3].

This project will provide important information regarding the potential CO_2 concentration that can be achieved in an electrolysis cell while also describing the gas properties in terms of chemistry and temperature. This information will help define the applicability of different potential solutions for subsequent CO_2 capture. The level of greenhouse gases in the atmosphere has rapidly risen since the aluminum industrial revolution. The principal gases associated with climate change are carbon dioxide and carbon monoxide. Carbon dioxide is considered the main greenhouse gas due to the significant amount of emissions released into the atmosphere [4]. The aluminum industry is responsible for significant carbon dioxide emissions, as it is the main gas emitted from the electrolysis cells due to the raw materials (petroleum coke and coal tar pitch) used in anode production. The intensity of these gas emissions depends on a multitude of factors such as the current efficiency (ε), cell amperage (I), the electrolysis cell structure, and the anode conditions, namely its ability to withstand O_2 and CO_2 oxidation. Efforts are being made on different levels to reduce GHG emissions, and this study investigates the behavior affecting CO_2 concentration specifically [5]. In this research, a three-dimensional model was created and solved using a numerical method employing a finite difference algorithm within the Ansys/Fluent software. The main objective is to investigate the distribution of gas pressure and CO_2 concentration in the space volume above the crust, under steady-state conditions for a specific set of operating conditions. The proposition of a pathway for potential CO_2 reduction is directly aligned with the main goals of this project. Using the numerical simulations developed, it will be possible to recommend alternative scenarios in which the dilution rate of carbon dioxide can be reduced while limiting the impact on fugitive emissions. The primary indicators examined for validation of the model encompass gas output velocity and concentrations, which are compared with industrial data obtained from previously documented sources in the literature. Additionally, gas collection efficiency is examined in relation to the structure of the gas gathering system and the operation of the electrolytic cell.

2. Literature Review

Many authors have studied the exhaust gas gathering efficiency and CO_2 capture simulation of aluminum electrolysis cells using numerical simulations and Computational Fluid Dynamics software. The Hall-Héroult process, while essential for aluminum production, emits a significant amount of CO_2 into the atmosphere. To address this issue and reduce CO_2 emissions from aluminum production, it is crucial to develop technologies for capturing and storing the CO_2 emitted during the process [6]. Simulation models are created using software like Aspen Plus and Aspen Hysys to evaluate CO_2 capture in aluminum production. In Aspen Hysys, a closed-loop model is used to simulate the CO_2 capture process, which is vital for addressing climate change concerns. These models allow for the analysis of different CO_2 concentrations and capture rates [7]. This research has provided valuable information on potential CO_2 concentrations achievable in electrolysis cells, as well as describe gas properties in terms of chemistry and temperature to define the applicability of potential CO_2 capture solutions. The proposal of a pathway for potential CO_2 reduction aligns directly with the main goals of this project. The aim of this investigation is to evaluate the potential for CO_2 capture from aluminum production by looking at conditions were the CO_2 concentration would be higher than 4 vol% [8].

CFD software is used to implement simulations of a 400 kA aluminum cell. Cell gas collection systems are studied, and the multi-physics field model for the aluminum electrolysis gas gathering system is established. The main conclusions are as follows: The cell has two short sides, called the tap end and the duct end. opening the tapping end side hooding panels has a greater impact on exhaust gas flow than opening the duct end side hooding panels. Due to this, the average flow rate in the two ducts declines and affects the exhaust gas flow rate, indicating that opening the cell hooding panels has little effect, and maintains gas stability under the hood of the electrolysis range of cell conditions that could favor a reduced CO_2 dilution rate while limiting the risk of fugitive emissions.

Finally, this work also highlighted that the base case operational scenario is likely much stronger than needed to prevent fugitive emissions under idealistic hooding conditions. While the real operations scenarios need to be taken into consideration, along with expected cell operations that will influence the opening of the hoods and tapping door. A periodic modulation of the exhaust pressure quickly appears as a suitable potential solution that could increase the CO_2 concentration in specific local regions of the electrolysis cell.

Future developments using this model will require thorough experimental in-situ validations in order to provide even more precise investigations regarding concrete or futuristic solutions to reduce the dilution rate of the carbon dioxide while mitigating the potential harm coming from fugitive emissions.

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