Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Spatial thermal condition in aluminum reduction cells under influences of electrolyte flow

Cheuk-Yi Cheung, Chris Menictas, Jie Bao, Maria Skyllas-Kazacos, Barry J. Welch*

School of Chemical Engineering, The University of New South Wales, UNSW, Sydney, NSW 2052, Australia

ARTICLE INFO

Article history:
Received 14 November 2013
Received in revised form 17 April 2015
Accepted 30 April 2015
Available online 15 May 2015

Keywords:
Aluminum reduction cells
Spatial ledge profile
Energy balance
Electrolyte flow
Individual anode currents

ABSTRACT

Electrolyte temperature and ledge thickness are two important variables in an aluminum reduction cell, which are often subject to local cell conditions, in particular, local convective heat transfer induced by electrolyte circulation even during normal operation. Understanding the spatial distribution of these two variables is important in the Hall Héroult process for effective alumina feeding to minimize process faults, and to maintain the material and energy balance, as they are coupled via the existence of the ledge layer. In this study, a three-dimensional dynamic model is developed to estimate the spatial cell thermal conditions, and the resulting ledge profile, by mapping a steady state electrolyte flow in the proposed discretized domain. This modeling approach allows the model to be expanded such that different process dynamics can be captured to achieve better estimation, where spatial information can be used to optimize cell operation.

1. Introduction

While work practices and individual anode current distribution are factors contributing to local thermal variations in an aluminum reduction cell (McFadden et al., 2001; Cheung et al., 2013), experimental works (Kristensen et al., 2005; Whitfield, 2003) have demonstrated that spatial convective heat transfer induced by electrolyte circulation also generates localized effects on the cell thermal condition (Utne, 1982; Haupin, 1997; Romerio et al., 2005). For instance, spatial temperature differences in an industrial reduction cell can range from an average of 971 °C at one end located away from feeding zones, to an average of 958 °C in the middle of the side channel at the same time under normal cell operation (Whitfield, 2003).

The flow pattern and velocity of the electrolyte are induced by the combined effects of the gas release pattern, the drag force from the metal pad, the thermal convection, and the magnetohydrodynamic force arising from the interaction between the magnetic fields and the electric current (Feng et al., 2010; Grjotheim and Welch, 1980; Doheim et al., 2008). As the factors described above can differ with varying cell design and anode configuration (Cooksey and Yang, 2006; Purdie et al., 1993; Richards et al., 2003), the effect on spatial thermal condition are distinct between different cell technologies (Whitfield, 2003).

This makes understanding the electrolyte temperature distribution induced by electrolyte circulation at individual cells important. It is not only because the feeding strategy can be adjusted to avoid over feeding alumina to the electrolyte at potential cool spots, but also measures can be taken to maintain an adequate and uniform layer of ledge for good cell operation as the ledge can mutually affect the cell thermal and material balance (Stam et al., 2008). The ledge is the frozen electrolyte which forms along the sidewall of the aluminum reduction cell.

Various thermal dynamic models have been developed to estimate cell dynamics under various cell operating conditions (Tikasz et al., 1994; Biedler, 2003; Yurkov and Mann, 2005; Jessen, 2008; Kolås and Støre, 2009; Gusberti et al., 2011). Although these models are different in terms of taking

* *Corresponding author*. Tel.: +61 2 9385 6755; fax: +61 2 9385 5966.
E-mail address: j.bao@unsw.edu.au (J. Bao).
http://dx.doi.org/10.1016/j.cherd.2015.04.034

Table 1 – Significant features of existing models.

Tikasz et al. (1994)	Incorporate 3 types of alumina for alumina balance calculation
Biedler (2003) and Jessen (2008)	Include heat loss from anode rods, deck plate into computation Apply first order dissolution rate equation
Yurkov and Mann (2005)	Incorporate 3 transformation phases of alumina for heat balance computation
Kolås and Støre (2009)	Consider emission and neutralization for the computation of AlF_3 mass balance
Gusberti et al. (2011)	Apply extended cell control volume for heat balance computation

different additional process features into consideration, most of them only compute the global temperature of important variables and overall ledge thickness. (Significant features of these models are listed in Table 1.) These models rely on the assumption of homogeneity on the states of the cell, i.e. they often treat layers of the electrolyte, the metal, and the ledge profile as homogeneous layers with uniform properties. Consequently local variations occurring in the reduction cell, in particular, spatial thermal effect caused by electrolyte circulation, are either inadequately described or ignored by the models. In order to compensate the effect, these models often employ enhanced thermal conductivities of the electrolyte and the metal (Bruggeman and Danka, 1990; Consiglieri and MuñIz, 2003). Taylor et al. (1996), on the other hand, incorporate electrolyte flow in their model. However, the model only computes overall response of electrolyte temperature and horizontal ledge profile, ignoring the spatial effect of flow on temperature and the ledge.

In this work, a three-dimensional thermal dynamic model incorporating spatial effect of electrolyte circulation on the temperature distribution within the cell as well as the horizontal ledge profile is presented. The model extends from the two-dimensional conduction model developed in the previous work (Cheung et al., 2013), and now includes crust layer and cell linings (as denoted as $k=2, \ldots, 4$, and $k=-2, \ldots, 1$ in Figs. 2 and 3, respectively, in Section 2.1), to calculate heat loss through the top and the bottom of the cell as a function of the spatial temperature gradient. The crust layer is an insulating cover present on top of the electrolyte, where its local thickness and temperature affect heat loss from the cell and subsequently the spatial energy balance. In order to investigate the spatial impact of convective heat transfer, a two-dimensional steady state electrolyte flow is mapped to the liquid region where the electrolyte and the metal are located, based on the proposed discretization. In this work, the impact of electrolyte circulation on the spatial thermal condition of the cell is studied by comparing the simulated results of two steady state electrolyte flows found in different cell technologies (flow patterns courtesy of the Industrial Collaborator, and CAETE Engenharia, Brazil, respectively). This demonstrates the importance of a dynamic model to capture local effects induced by electrolyte circulation in order to achieve better estimations of the distributed process, which has normally been ignored by the traditional modeling approach.

2. Modeling approach

2.1. *Three-dimensional model*

The three-dimensional model is built based on the two-dimensional conduction model developed previously by Cheung et al. (2013). The two-dimensional model considered three major regions: the liquid, the ledge and the sidewall regions. The liquid region consisted of both electrolyte and metal layers as well as components immersed within the liquid, including anodes. Both the liquid and the ledge regions were discretized into a two-dimensional array of subsystems based on anode locations as illustrated in Fig. 1, where two-dimensional heat transfer was computed. Unlike the liquid and the ledge regions, the sidewall region was treated as one block, assuming heat transfer at the cell sidewall to be one dimensional. As the earlier two-dimensional model did not include top crust layer and cell linings, heat loss through the top and the bottom of the cell was estimated based on the heat loss percentage derived from a typical industrial reduction cell (Grjotheim and Welch, 1980).

In the three-dimensional model, further development has been made based on the proposed discretization in the two-dimensional model. The sidewall region is discretized to compute spatial heat loss to the outside of the cell. The three-dimensional model now includes the cell lining and the crust layer in order to capture conductive heat transfer in the z direction. The model structure proposed in this work provides the freedom for model expansion to include additional local dynamics, as demonstrated in the later section which maps a steady state electrolyte flow to compute its impact on the spatial temperature and ledge profile.

The general heat equation in the three-dimensional model is given as,

$$\frac{d(m_{(i,j,k)} \cdot \bar{c}_{(i,j,k)} \cdot T_{(i,j,k)})}{dt} = Q_{cond} + q^{net}_{(i,j,k)}, \quad (1)$$

where

$$Q_{cond} = q^{n}_{(i-1,j,k)} + q^{n}_{(i+1,j,k)} + q^{n}_{(i,j-1,k)} + q^{n}_{(i,j+1,k)} + q^{n}_{(i,j,k-1)} + q^{n}_{(i,j,k+1)}, \quad (2)$$

for all $i=1, \ldots, N_x$, $j=1, \ldots, N_y$, and $k=-2, \ldots, 4$, where i and j are the indices of the subsystems in the x and y directions, with total numbers of subsystems N_x and N_y respectively. Each k defines a different region in the z direction: horizontal layers of the cell lining regions ($k=-2, \ldots, 1$, Section 2.3); the liquid and ledge region ($k=1$, Section 2.2.1); the region where the part of an anode that is not immersed in the electrolyte ($k=2$, Section 2.2.2), the crust region ($k=3$, Section 2.2.3) and the crust surface region ($k=4$ in Section 2.2.3) as shown in Figs. 2 and 3. It should be noted that the sidewall at Level $k=1$ is at the same level as the liquid region, yet they have a different horizontal discretization which will be discussed in later sections.

Eqs. (1) and (2) are the approximate solution of the heat equation based on finite difference method. The equations compute the change of the temperature of a subsystem, $T_{i,j,k}$, based on the spatial coordinates defined by the proposed discretization. It consists of several terms to account for the heat transfer rate at each interface of the subsystem (i,j,k) from immediate neighboring subsystems in different directions, as denoted by q^n. The superscript, n, denotes different cases of heat transfer at a different interface at a different level in the