3D Thermo-Electric Modelling of Aluminium Reduction Cells Including Equilibrium Ledge Profile Prediction

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Abstract

Modern aluminium electrolysis cell designs for high amperage, low energy consumption and power flexibility require detailed investigation of spatial heat generation and distribution in the cell as well as of the cooling conditions at the shell outside. To increase the predictive power of thermo-electric modelling for aluminium reduction cells and to streamline the workflow between modelling and detailed design, a parametrized Autodesk Inventor CAD interface was developed and coupled to an ANSYS Workbench thermo-electric simulation. The geometry model includes most details of anode and cathode assemblies as well as of the pot shell. An elaborate iteration scheme is used to calculate equilibrium ledge profiles. This allows for more realistic results that are not compromised by geometrical simplifications or simplified boundary conditions.

Keywords: Computer-aided design (CAD), simulation, cell design, heat balance, thermo-electric modeling

1. Introduction

Thermal and electric fields in aluminium reduction cells are strongly coupled due to non-linear material properties, extremely high electric currents between 100 and 800 kA and operation temperatures close to 960 °C. Thereby, the thermal stability of an aluminium reduction cell depends on the solidification of electrolyte (ledge) at the inner cell walls, which protects the cell from corrosion and dissolution.

Since the early 1990s partly or full 3D thermo-electrical simulation approaches based on ANSYS® are used in the aluminium industry to predict the heat and voltage balance of cell design upgrades [1, 2]. With improving computer performance, the simulation approaches were extended for transient applications like cell preheating and cathode erosion [3] and coupled to outer convection cooling and inner bath/metal flow simulation approaches [4 - 6]. Detailed analysis of thermo-mechanical and thermo-electro-mechanic effects at anode and cathode blocks and connections followed in the recent years completing the picture [7 - 10].

Today thermo-electrical/mechanical simulations are a common production tool in design and operation improvement which is tightly connected to the local CAD system for realistic geometries. In this paper an integrated and automated approach is presented covering the full span width from CAD design to thermo-electrical/mechanical cell simulation.

The fully automated tool imports the cell geometry from a CAD model into the simulation environment, including the pot shell as well as cathode and anode assemblies. The program

continues by defining model settings, boundary conditions and standard results visualisation and initiates the simulation. The solver routines encompass an elaborate iteration scheme with alternating thermal-electric and structural-mechanical solutions, supported by mesh non-linear adaptivity, to finally obtain a consistent thermal-electric solution at ledge phase equilibrium.

This paper is structured as follows: Section 2 explains the simulation approach in general, such as interlinks to CAD software and the advantages of realistic and detailed model geometries. To underline this, the role of welding seams in the pot shell of the Neuss smelter is given as an example. The ledge calculation scheme is discussed as well. Section 3 gives an impression on typical calculation results. Finally, a conclusion and an outlook are given in Section 4.

2. Thermo-electric simulation method

The primary purpose of a cell design tool is the calculation of the heat balance, which underlies, for pots in thermal balance, the following equation:

$$Q_{inn} + Q_{out} = 0 \tag{1}$$

where Q_{inn} describes total inner heat input to the cell, and Q_{out} denotes the heat losses to outside over the potshell, superstructure, hooding, and so on.

It should be noted that the main heat source in the cell, the Joule heating, is a locally varying quantity. Thus, a purely thermal heat conduction problem with averaged Joule heating contributions would not adequately describe the spatial heat distribution within the cell. Instead, a coupled thermal and electric approach has to be chosen based on temperature-dependent individual thermal and electrical conductivities, which involves the local currents within the pot. The following coupled equations constitute the stationary heat conduction problem including Joule heating terms:

$$-\nabla(\lambda \nabla T) = \sigma(\nabla V)^2 \tag{2}$$

$$\nabla(\sigma \nabla V) = 0 \tag{3}$$

Here, λ and σ denote temperature-dependent thermal and electrical conductivities, respectively, while $T = T(x, y, z)$ and $V = V(x, y, z)$ are the solution functions of the temperature and electric potential defined for space variables x, y, z. For further mathematical insight on coupled-field equations solved in a FE thermo-electric analysis in ANSYS, see, e.g., Antonova and Looman [11].

2.1. Integrated Modelling Approach

To enable a wide functionality based on a realistic cell geometry including full shell, cathode and anode details, an integrated modelling approach was chosen. In this way, the geometry can be automatically generated by the CAD system, Autodesk Inventor, based on a parameter list and controlled by a graphical user interface (GUI). After setting up the geometry and applying the material properties, the necessary boundary conditions are selected in the GUI and the simulation is automatically initiated within ANSYS Workbench (see Figure 1). Upon finishing the calculations, result tables with design information and a selection of result plots are generated.

Several benefits accompany this approach. The high level of geometry parametrization allows generating detailed CAD models and interlinking these with a state-of-the-art simulation environment. Thereby, manual user work is solely done within the GUI, thus, without the

6. References

1. Marc Dupius, Imad Tabsh, Thermo-electric analysis of the grande-baie aluminum reduction cell, *Light Metals* 1994, 339-342.
2. Detlef Vogelsang et al., From 110 to 175 kA, Retrofit of VAW Rheinwerk, Part I: Modernisation Concept, *Light Metals* 1997, 233-238.
3. Marc Dupuis, Development of a 3D transient thermo-electric cathode panel erosion model of an aluminum reduction cell, CIM 2000, 169-178.
4. Detlef Vogelsang, Ingo Eick, Dimensioning of cooling fins for high-amperage reduction cells, *Light Metals* 1999, 339.
5. M. Dupuis, V. Bojarevics, J. Freibergs, Demonstration thermo-electric and MHD mathematical models of a 500 kA Al electrolysis cell, *CIM 2003*, 3-20
6. Gennady V. Arkhipov, Alexander V. Rozin, The aluminum reduction cell closed system of 3D mathematical models, *Light Metals* 2005, 589-592.
7. Marc Dupuis, Development and application of an ansys based thermo-electro-mechanical collector bar slot design tool, *Light Metals* 2011, 519-524.
8. D.R. Gunasegaram, D. Molenaar, A fully coupled thermal-electrical-mechanical transient fea model for a 3D anode assembly, *Light Metals* 2013, 1341-1346.
9. Mathieu Gagnon et al., Optimization of the cathode collector bar with a copper insert using finite element method, *Light Metals* 2013, 621-626.
10. Dag Herman Andersen and Hogne Linga, Evaluating the crack resistance of carbon anodes: Implementation of a measurement system for tensile strength and fracture toughness, *Light Metals* 2015, 1123-1128.
11. E. E. Antonova and D. C. Looman, Finite elements for thermoelectric device analysis in ANSYS, *ICT 2005. 24th International Conference on Thermoelectrics,* 2005, 215-218.
12. Asbjørn Solheim, Nils-Håvard Giskeødegård, and Nancy J. Holt, Sideledge facing metal in aluminium electrolysis cells: Freezing and melting in the presence of a bath film", *Light Metals* 2016, 333-338.