COMSOL Multiphysics® Simulation For Designing Energy-Efficient Aluminium Reduction Cells

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Abstract

The increasing global demand for aluminium, coupled with its vital role in various industries, necessitates the development of energy-efficient production processes. The aluminium reduction process, which converts alumina into primary aluminium by electrolysis in a cryolite-based electrolyte, is highly energy-intensive. The design of efficient aluminium reduction cells plays a critical role in reducing energy consumption. The design and optimization of these cells require a thorough understanding of complex physical phenomena, including thermal-electrical coupling, electromagnetics, magnetohydrodynamics (MHD), computational fluid dynamics (CFD), and thermo-mechanical interactions.

To accurately capture the intricacies of aluminium reduction cell design, a modelling approach that accounts for the diverse components of the cell at various scales is employed. While certain aspects, such as thermal balance for the selection of proper cathode lining, can be estimated using 3D slice and quarter models, the calculation of magnetic fields, required for busbar design, necessitates a comprehensive representation of the full smelter. This multi-scale modelling approach enables a comprehensive analysis of the energy-intensive aluminium reduction process, facilitating the optimization of cell design parameters to achieve higher energy efficiency.

Given the multiphysics nature of the aluminium reduction process, the utilization of various COMSOL® modules becomes essential for a comprehensive simulation approach. Modules such as Heat Transfer, AC/DC, CFD, Electrochemistry, and Structural Mechanics are employed to address the diverse physical phenomena involved. A coupling of the Heat Transfer Module and the AC/DC Module enables the analysis of thermal-electrical behaviour, temperature and voltage drop distribution in the reduction cell which are required for cathode lining design and specific energy consumption optimization of the aluminium cell. The coupling of the AC/DC Module and the CFD Module facilitates the comprehensive study of electromagnetics and the subsequent MHD behaviour within the aluminium reduction cell. This coupled analysis is crucial for designing an effective busbar system, which is essential for ensuring MHD stability and optimal cell performance. The coupling of the Electrochemistry Module and the CFD Module in COMSOL Multiphysics® facilitates the simulation of anode bubble generation, electrochemical carbon anode consumption, and their impact on fluid dynamics in the electrolyte. This integrated simulation approach is valuable for optimizing anode design.

The CFD Module can be used to design an effective fume-capturing system that ensures all emissions are directed to a fume treatment plant rather than being released into the environment. The Structural Mechanics Module, deployed for modelling of the thermo-mechanical behaviour of the cathode lining and potshell in aluminium reduction cells, ensures their integrity and prolonged cell life. In addition to these modules, the development of custom apps using the Application Builder in COMSOL® empowers the operators to make quick decisions without relying solely on the research and development modelling team.

This presentation shows a comprehensive approach to designing aluminium reduction cells using different modules of the COMSOL Multiphysics® software.