Validation of Anode Model for Voltage Drop Mitigation Studies

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Abstract

In aluminum smelters, the anode of a typical reduction cell has been widely reported as a location where significant amount of energy is wasted. These devices need optimization and a practical tool for this is the thermo-electro-mechanical (TEM) finite element model. In view of developing a computational tool fit for such optimization efforts, this study focuses on calibrating the contact stiffness factor (CSF) and on validating developed TEM models of the 4- and 8-flute anodes. Plant measurements of the anode stub to carbon (STC) and total (TVD) voltage drop, across the lifespan of the anode, were made for model validation. Calibration of the numerical model showed that CSF of 0.15 - 0.2 is adequate for the 8-flute anode while CSF of 0.5 is adequate for the 4-flute anode. Using these CSFs, results show that onsite measurements match the STC voltage drop and TVD, calculated by the TEM model. Overall, this article is an update on our finite element modeling of the aluminum-reduction cell anode.

Keywords: Aluminum reduction cell anode; anode model validation; anode voltage drop; contact stiffness factor.

1 Introduction

The anode of the aluminum-smelter has been recurrently singled out as a part of the reduction cell, which holds some potential for reducing energy consumption, if properly optimized [1,2,3,4,5,6,7,8]. As connections between the steel-stubs and the carbon blocks are made by pouring molten cast iron in the space between both materials, shrinkage of the cast iron connector (thimble) introduces imperfection to the stub-carbon contacts. In addition, the toe-in of the tripod stub [9] and suspension of the anode from the busbar [10], also contribute to the imperfection at the interface. From an electrical perspective, these imperfections denote an increased contact resistance and therefore, increased voltage drop and energy consumption of the anode.

Minimizing these imperfections is the ultimate aim of most studies in this line of research. The literature in this field can be summarized as early lab-scale experimental works focused on measuring the thimble-carbon contact voltage drop as a function of temperature and pressure [11,12] and later work focused on developing finite element models of the anode setup [10]. In between, some researchers attempted carrying out more experiments to calculate the voltage drop at these contacts as a function of stub size [8]. This was then followed up with computational models with the same stub-reduction strategy in view [9]. Overall, to adequately simulate the anode physical operation, coupling of the thermal, electrical, and structural fields has proven to be the key for such models.

TEM models developed for the anode have shown a lot of promise; however, till date, these tools still have limitations. The typical drawbacks of the available anode models are:

1. Inadequate modeling of the casting process,
2. Use of wrong location for fixed constraint,
3. Lack of transient analyses,
4. Inadequately modeled thimble-carbon electric contact resistance,
5. Excessive computational time and
6. Lack of validation with plant measurements.

As such, the future should be directed at eliminating all these drawbacks by:

1. Modeling the thimbles reference at its casting temperature to ensure adequate room temperature thimble-carbon air gaps are solved by the computational code,
2. Applying the fixed constraint boundary at the top of the stub in order to adequately model the anode suspension from the busbar,
3. Modeling the anode from the time it is newly inserted till when the carbon block is fully consumed and removed (end of life),
4. Using deduced and validated relations to model the thimble-carbon contact voltage drop as a function of contact temperature and pressure, from our previous study [2],
5. Applying an expedited and validated coupling computational technique [1,2] and
6. Using plant anode voltage measurements to validate our models.

In our previous work [1], we considered the aforementioned drawbacks, but our efforts did not include complete model validations and transient considerations. As such, conclusions could not be drawn about the efficacy of the energy saving strategies assessed. Also, our results revealed strong dependence of the voltage drop results on the CSF, which highlighted the need for further calibration with plant measurements for quantitatively accurate results. This is an important consideration in anode modeling, which is most often completely overlooked. As mentioned earlier, the thimble-carbon interface is imperfect; hence, a mathematical formulation that allows for nodal interface separation is required to adequately model the contact behavior and hence electrical and thermal contact resistance. As such, the frictional contact formulations, which allow for nodal contact sliding, opening and closing, depending on the contact force, are befitting. However, these formulations are typically controlled by either the Pure Penalty or the Augmented Lagrangian model [13], which model the contacts as a hypothetical spring with the contact gap directly proportional to the contact pressure. The proportionality constant of this relation is the contact stiffness factor (CSF). The contact pressure and hence electrical contact pressure are dependent on CSF as such; the calculated voltage drop is dependent on the CSF utilized. The only way of knowing the correct CSF is by calibration with measurements; hence, calibration is a necessary step for the development of quantitatively accurate anode models [1] and this is also an important consideration in the present work.

Overall, this work reports the development, calibration and validation of a transient TEM finite element model of the aluminum reduction cell anode. The model formulation is based on our previously developed anode model [1], and calibration and validation are carried out using plant measurements on operating pots.

2 Mathematical Model

The domain and boundary conditions of the developed anode model is presented in Figure 1. The boundary conditions of Figure 1 are based on the beginning-of-life anode; however, we

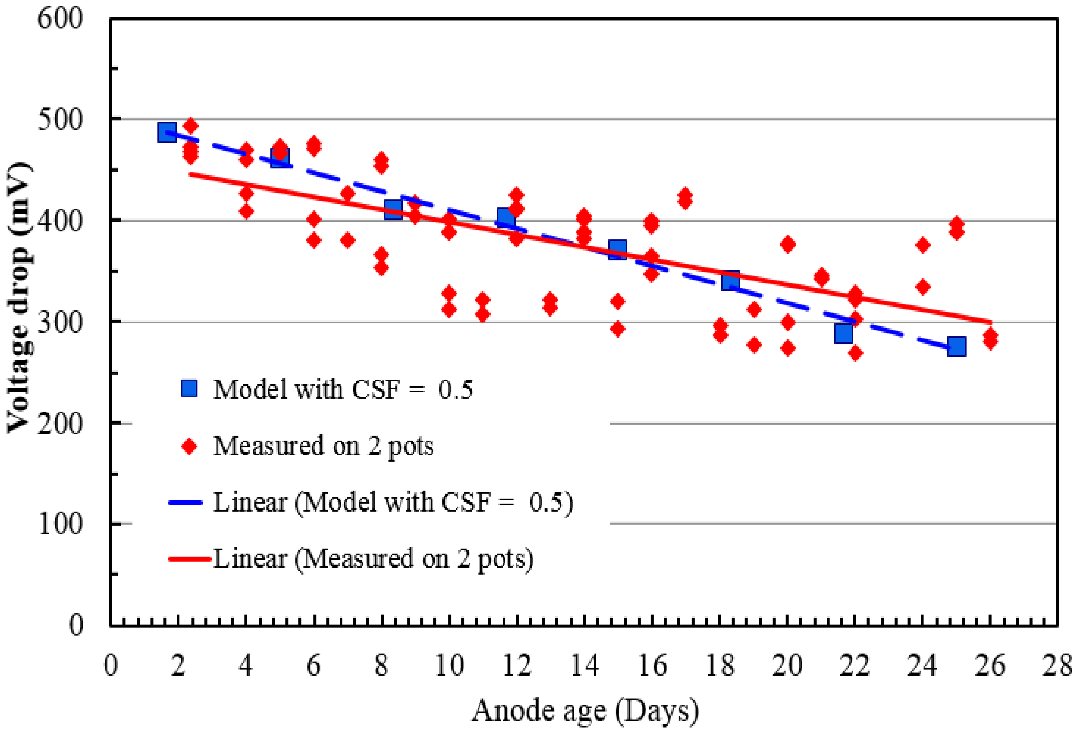

Figure 9. Total anode voltage drop in anodes with 4 flutes.

5 Conclusion

In this study, we have developed and validated a transient anode model of an aluminum-reduction cell, for the whole life of the anode. The contact stiffness factor (CFS) is used as an adjustable parameter for model validation with stub-to-carbon (STC) voltage drop and total voltage drop (TVD).The model validation shows that CSF in the range of 0.15 to 0.5 is adequate for the anode model, with CSF of 0.15 - 0.2 giving best fit for the 8-flute anode and CSF of 0.5 for the 4-flute anode. Numerically calculated STC voltage drop and TVD agree well with plant measurements.

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7 References

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