# Anode design modeling for improved energy efficiency

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**Abstract**



In aluminum reduction technology, a substantial portion of the anode's voltage drop is a consequence of imperfect contact between the cast iron thimble (connector) and the anode's carbon block. A useful tool for optimising these contacts, in order to improve the anode's energy efficiency, is the electro-thermo-mechanical (ETM) mathematical model. Using the ETM, this study elucidates on the underlying problem of voltage drop within the anode of an aluminum reduction cell and presents alleviation strategies. Adequate correlations for the temperature and pressure dependent electrical contact conductance (ECC) were utilised to facilitate realistic results. Two voltage drop mitigation approaches were considered: (i) metallurgical modifications of the steel stub for favorable thermal and mechanical properties; and (ii) geometrical modification of the thimble to maximise real-contact area. Results show that both strategies could reduce the electric contact resistance and hence, reduce the overall anode voltage drop. Strong dependence of the results on the Contact Stiffness Factor (CSF) suggests the need for further calibration with onsite measurements for quantitatively accurate results. Also, as our model is based on fresh anodes, conclusions cannot be drawn about the efficacy of our strategies in saving energy as the anode life approaches its end. Overall, this article documents our experience in developing ETM models of the anode.

**Keywords:** Aluminum reduction; anode voltage drop; electrical contact resistance.

## 1 Introduction

The anode assembly of the aluminum reduction cell is usually coupled by connecting steel stubs to a carbon block using a molten cast iron thimble. However, as cast iron shrinks during solidification and cast iron does not wet carbon, a gap arises between the thimble and the carbon block. This imperfect contact contributes to the voltage drop of the cell during operations, which could cost a typical smelter up to USD 2.2 million per annum. This is a magnitude that legitimately necessitates concern. Taking a deeper probe at this problem, the origin of the voltage drop can be traced to the presence of asperities on real surfaces when contact is attempted; only localized metallic contacts are made and these act as the conducting path for the transfer of electrical current [1]. A combination of these conducting sites across the contact surface forms the "real-contact area", which is the major parameter to enhance in order to minimise voltage drop at the contact interface [1, 2].

Experimental studies focused on mitigating this voltage drop can be traced back to the 1970s [3, 4]. The most imperative findings from early studies were relationships between the electrical contact resistances and the thermo-mechanical loading experienced at the contact [3, 4, 5, 6]. In these studies, dependence of the electric contact resistance on the contact's thermodynamic conditions is unequivocally reported. More recent experimental studies in this line have corroborated earlier findings [7, 8] and attempted to deduce equations which describe the electric contact resistance as a function of contact temperature and pressure [9, 10, 11]. However, the high cost of these experiments, coupled with the repetitive nature of optimisation studies, precluded the development of voltage drop mitigation strategies using this approach.

Mathematical modelling, which has experienced significant growth in the past two decades, has also gained huge attention in the aluminum research and development community. Consequently, efforts in mitigating anode voltage drop have been extended to computational models. The electro-thermal (ET) models of the anode developed in the 1990s [12, 13] pioneered such works, but omission of a mechanical model in Dupuis [13] and Hou et al [12] limited the robustness of their analyses. Richard et al's electro-thermo-mechanical (ETM) coupling [14] presented a more rigorous approach. Aside from incorporating the pressure and temperature dependent electric contact resistance, Richard et al's study [14] established a technique for estimating the initial separation between carbon and cast iron at ambient temperature. This technique is now widely applied in developing finite element models [15]. Richard et al [14] showed that increasing the effective cast iron mass (either by lengthening the flutes or by adding more of them) results in a reduced voltage drop until a minimum is achieved. Beyond this value, adding more cast iron led to a rapid deterioration of the anode's energy efficiency. An alternate study revealed that, despite the increased nominal surface area and mass of the thimble, the resulting anode voltage drop was found to increase slightly due to the decrease of contact quality [16]. This finding correlates with other studies, which showed that an increment in the thimble surface area does not guarantee a reduction in contact voltage drop [17, 16]. This suggests that the relation between the temperature, pressure and, the real-contact area variables is highly non-linear. Undoubtedly, the complexity of deciphering the relation between the contact's thermodynamic conditions and its real-contact area has greatly hampered progress in this field. Till date, a general conclusion on stub-hole design has not been made – no real solution has been proposed, with the majority of the modeling studies being stopped at portraying the prospect of the finite element analysis (FEA) tool [10, 17, 14, 16].

In maximising the real-contact surface area and pressure, a closer look has to be taken into the macroscopic structural deformation of the anode stub. Fortin et al [18] demonstrated how the typical tripod (yoke) configuration of the steel stub has a significant effect on its thermo-mechanical deformation. As shown in Figure 1, due to the thermal-expansion in the horizontal direction, with the stubs immobile at the bottom, the outer stubs tilt to generate a pressure bias on the carbon block to create a phenomenon known as the "toe-in" effect. This generates an unsymmetrical contact area and pressure which have distributions that are further complicated by the transfer of the anode assembly's weight to the flutes due to the "hanging" of the anode set-up from the cell's superstructure.

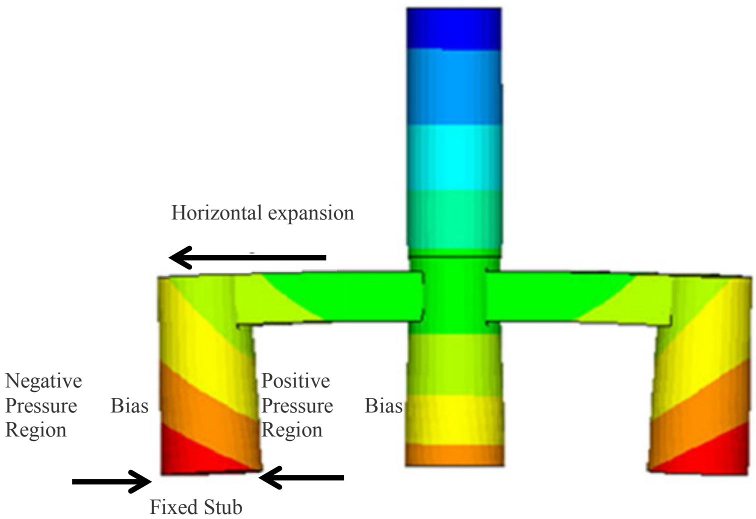


**Figure 1. Toe in effect of the tripod (yoke) steel stub configuration (magnified by 30) [18].**

Very little can be done to improve the real-contact area at the negatively-biased pressure region. Hence, in mitigating the contact voltage drop for the tripod configuration stub, efforts should be focused on maximising the contact pressure at the positively-biased pressure region. This requires an

**Figure 9. Voltage drop comparison for modified steel stub metallurgy.**

As an increase in CSF signifies an increase in the stiffness of a hypothetical spring placed between the contacting surfaces, less separation and higher contact pressure are expected at higher CSF values. Although experimental calibration is required to calibrate the model accurately for an adequate CSF, based on previous experience in developing this type of model [11] and previous estimates of the contact voltage drop of the anode [17], the right CSF value is expected to fall between 0.1 and 1. Based on this premise, we ranked the designs presented in Figure 8 from lowest to highest contact voltage drop as: Typical Thimble (Inverted flutes), Typical Thimble (4 flutes, Inverted flutes), Typical Thimble, Typical Thimble (4 flutes), Mushroom Thimble. Apparently, as previously hypothesized, inversion of the flute direction reduces the contact voltage drop.

Figure 9 shows that increments in the stub material's TEC reduce the contact voltage drop until our estimated adequate TEC value is attained. As the thermal expansion coefficient of the steal stub is increased, the gap between the thimble and the carbon is reduced, hence reducing the contact voltage drop. However, when the gap is fully closed, further increments cause penetration of the thimble in the carbon, which is translated by our model as a negative contact gap. For simplicity, at gaps of 0 mm and below, the contact pressure is modelled as 0 Pa, hence penetration is not adequately taken into account. This is why the model portrays increments in contact voltage drop as the TEC value exceeds the "Adequate TEC". As no fracture mechanism was included in our model, we cannot tell if the thimble mechanical integrity was sustained at the increased pressure.

Although both strategies portray an improvement in energy efficiency, we cannot draw conclusions on the performance of these designs when used in an anode reaching its end-of-life. As the carbon block is consumed with anode age, the thermodynamic conditions at the thimble-carbon interface change, which alters the validity of the current model. Further studies are recommended to cover the life span of the anode in order to ensure that energy saving strategies are applicable through-out the anode life.

## 4. Conclusion

In this study, we present our developed TEM FEM for modelling the aluminum reduction cell's anode assembly. Using the TEM, we evaluate the fitness of two voltage drop reduction approaches: thimble design and stub steel thermal expansion. The effect of varying the model boundary conditions, CSF and thimble mass on the contact voltage drop were also highlighted. Results showed that there is room for reducing the contact voltage drop by changing the thimble flute design, but strong dependence of the results on the CSF and lack of a fracture mechanism in our models suggest the need for further calibration with experiments.

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## 6. References

1. M. Braunovic, "Power connections," in Electrical Contacts, Boston, P. Slade and M. Dekker, 155, p. 1999.
2. R. Holm, Electric Contacts; Theory and Applications, New York: Springer, 1967.
3. R.W. Peterson, "Studies of stub to carbon voltage," *Light Metals,* 1978, pp 367-378.
4. W. Peterson, "Temperature and voltage measurements in Hall cell anodes," *Light Metals,* 1976, pp 365-382.

5. D.G. Brooks and V.L. Bullough, "Factors in the design of reduction cell anodes," *Light Metals ,* 1984, pp 961-976.
6. P.J. Rhedey and L. Castonguay, "Effects of carbonaceous rodding mix formulation on steel-carbon contact resistance," *Light Metals,* 1985, pp 1089-1105.
7. M. Sørlie and H. Gran, "Cathode collector bar-to-carbon contact resistance," *Light Metals,* 1992, pp 779-787.
8. S. Wilkening and J.Cote, "Problems of the Stub- Anode Connection," *Light Metals,* 2007, pp 534- 542.
9. D. Richard, M. Fafard, R. Lacroix, P.l Cle´ry and Y. Maltais, "Carbon to cast iron electrical contact resistance constitutive model for finite element analysis," *Journal of Materials Processing Technology,* vol. 132, 2003, pp 119-131.
10. D. Molenaar, K. Ding and A. Kapoor, "Development of industrial benchmark finite element analysis model to study energy efficient electrical connections for primary aluminium smelters," *Light Metals,* 2011, pp 959-990.
11. A.T. Brimmo and M.I. Hassan, "Modeling the Electrical Contact Resistance at Steel-Carbon Interfaces," *JOM,* 2015, pp xx-yy.
12. T.X. Hou, Q. Jiao, E. Chin, W. Crowell and C. Celik, "A numerical model for improving anode stub design in aluminum smelting process," *Light Metals,* 1995, pp 755-761 .
13. M. Dupuis, "Computation of aluminum reduction cell energy balance using Ansys finite element models," *Light Metals,* 1998, pp 409-417.
14. D. Richard, M. Fafard, R. Lacroix, P. CleHry and Y. Maltais, "Aluminum reduction cell anode stub hole design using weakly coupled thermo-electro-mechanical Finite element models," *Finite Elements in Analysis and Design,* vol. 37, 2001, pp 287-304 .
15. H. Fortin, M. Fafard, N. Kandev and P. Goulet, "FEM analysis of voltage drop in the anode connector assembly," *Light Metals,* 2009, pp 1055-1059.
16. D. Richard, P. Goulet, O. Trempe, M. Dupuis and M. Fafard, "Challenges in the stub hole optimization of cast iron rodded anodes," *Light Metals,* 2009, pp 1067-1072.
17. M. Dupuis, "Development and application of an Ansys® based thermo-electro-mechanical anode stub hole design tool," *Light Metals,* 2010, pp 433-438.
18. M. Reverdy, A. Zarouni, J. Faudou, Q. Galadari, S. A. A.A. Zarouni, K. Al-Aswad, M. Al-Jallaf, W. Al-Sayed and V. Potocnik, "Advancements of Dubal High Amperage Reduction Cell Technologies," Light Metals, 2013, pp 553-556.
19. F.P. Incopera, D.P. Dewitt, T.L. Bergman and A.S.Lavine, Fundamentals of Heat and Mass Transfer, Hoboken, New Jersey: John Wiley and Sons, 2007.
20. P. Kohnke, "Theory reference for Mechanical APDL and Mechanical Applications," ANSYS Inc, Canonsburg, PA, 2009.
21. J.C. Simo and T.A. Laursen, "An augmented Lagrangian treatment of contact problems involving friction," Computer and Structures, Vol. 42, No. 1, 1992, pp. 97-116.
22. D. Richard, Conception des tourillons d'anode en usage dans une cuve de Hall-Héroult à l'aide de la méthode des éléments finis, M.Sc. Thesis, 2000, Université Laval, Quebec, Canada.