Impact of TE-MHD Coupling on Cell Performance

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Abstract

Metal velocity and metal upheaval have a significant effect on the temperature field in an aluminium reduction cell, and consequently on the ledge shape which in turn influences current density and metal velocity. This so-called coupling between thermal-electric (TE) and magneto-hydrodynamic (MHD) effects has an impact on the performance of the cell and evolves with increasing line amperage. Results of TE-MHD calculations on a full 3D cell show the importance of this coupling on the variable fields. Scenarios at different amperages are compared as well as the scenario in which the ledge variations induced by the coupling are compensated for by adjusting the heat extraction around the cell. The numerical model used in this study solves the full heat equation including convection and turbulent conductivity of the liquid bath and metal. The opportunity to mitigate MHD effects and/or compensate them thermally is discussed in the perspective of ledge control and cell performance.

Keywords: Modelling, TE-MHD coupling, Temperature field, Ledge shape.

1. Introduction

The modelling of the TE-MHD coupling in an aluminium reduction cell has been tackled in different ways over the years. Early attempts [1] resorted to weak coupling to model the heat flux at the liquid bath-ledge and metal-ledge interfaces. Velocity dependent heat transfer coefficients were used to account for the convection of heat. Variation of the ledge profile along the cell sides was limited and had a marginal impact on the velocity field. Some years later, a similar approach to the present one was implemented in the Alucell software [2], solving the transient heat equation formulated in enthalpy. The full 3D cell problem requires to solve Maxwell equations for the electrical potential and magnetic induction, Navier-Stokes equations for the pressure and velocity and the heat equation for the temperature. It makes a total of 9 unknown scalar fields complemented by boundary and interface conditions. The in-house MONA software [3], specialized in the modelling of the aluminium reduction cell, solves the 3D strong coupling of the 9 unknowns and predicts the ledge shape and metal surface simultaneously. MONA software can also be used to compute the diffusion of alumina in the bath and the MHD stability of the cell (growth factor of metal pad oscillations).

In the present work, the stationary heat equation – Equation (1) – formulated in enthalpy – Equation (2) – and Robin non-linear boundary condition – Equation (3) – are solved by means of the Finite-Element (FE) Method.

The first term on the left in Equation (1) is the heat advection term (TE-MHD coupling) whereas the second term is the heat diffusion term. The term on the right is the heat source term. Numerical oscillations caused by the convection term are prevented using a decentering SUPG (Streamline Upwind Petrov-Galerkin) technique with shock-capturing parameters [4].

$$\boldsymbol{v}\cdot\boldsymbol{\nabla}H - div(\lambda\boldsymbol{\nabla}\mathrm{T}) = q \tag{1}$$

$$H(T) = \rho C_p T + \rho L f_l \tag{2}$$

$$\lambda\boldsymbol{\nabla}T\cdot\boldsymbol{n} = \alpha(T)(T - T_\infty) \tag{3}$$

where:

v	velocity, m/s
H	enthalpy, J/m^3
λ	thermal conductivity, W/(m·K)
T	temperature, K
q	Joule heat source, W/m^3
ρ	density, kg/m^3
C_p	specific heat, J/(kg·K)
L	latent heat of fusion, J/kg
f_l	liquid fraction
n	unit vector normal to boundary
α	heat transfer coefficient, W/(m^2·K).

As in reference [2], the FE mesh is refined in the bath and metal parts where the solidification takes place (see Figure 1). For the calculation of the magnetic induction, both the studied and neighboring cells are modeled in full 3D whereas cells further away in the potline(s) are modelled by means of 3D wireframe elements. Temperature dependent material properties are considered while contact resistances and heat transfer coefficients at mesh boundaries (*i.e.*, free surfaces) are calibrated.

Heat transfer coefficients applied to the external surfaces of busbars, collector bars (outside the shell), shell bottom, shell sides and anode cover are calibrated separately whereas in reference [2], the heat transfer coefficient of shell sides is further differentiated between upstream (US) and downstream (DS) sides and corners. In liquid parts, turbulent viscosity, and thermal conductivity dependent on velocity gradients are included.

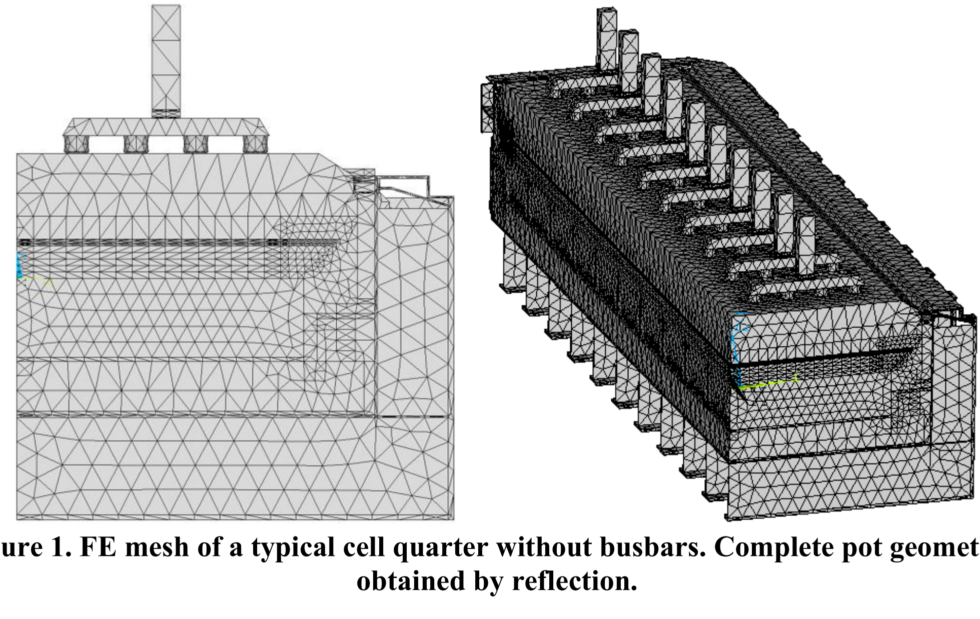

Figure 1. FE mesh of a typical cell quarter without busbars. Complete pot geometry is obtained by reflection.

The computed scenario – see Figures 2 c), 3 c) and 5 c) – goes beyond the actual test since heat extraction is adjusted to smoothen not the temperature but the ledge variations along the sidewalls themselves as well as between upstream and downstream sides. The results show that the thicker ledge region on the upstream side is significantly reduced. Interestingly, the corresponding shell temperature profiles are not uniform, see Figure 5 c). To compensate for the positive convection term (heat sink) on the upstream side, higher temperatures are needed on the shell sidewall to achieve a thinner ledge. It indicates that the ledge shape of the cells documented in Figure 6 was made more uniform but only partially.

The smoother ledge shape leads to higher metal velocity in the vicinity of the US sidewall center (average and maximum velocities are higher, see Figure 3). It agrees with our calculations showing that velocity is higher if there is no ledge.

3. Conclusion

Ledge shape is not monitored on a routine basis in aluminium smelters but is indirectly followed up through shell temperature measurements and Si content analysis of the tapped metal. Ledge is essential to pot operation as it protects the cell lining from bath corrosion, but it may destabilize the cell if it freezes the cathode surface. The modelling tools used in this study help at better understanding the interaction between the temperature of the liquid parts and their velocity distribution. The impact of amperage on the cell status is highlighted as well as the possibility to adjust heat extraction around the cell to make the ledge shape more uniform. Just as metal velocity disturbs the cell, enhancing MHD instability and metal reoxidation, its pattern affects the temperature field and determines the ledge shape. Reducing high metal velocity through operation (metal level) and/or by cell design (anode dimensions, cathode and busbars designs) will be beneficial to the cell. Adjusting heat extraction around the cell (shell design, forced convection) is also an option to counteract the effect of MHD on the thermal state of the cell. After testing many numerical schemes, the decentering SUPG technique with shock-capturing parameters [4] proved to be a robust solution for predicting the ledge shape in presence of TE-MHD effects. It is presently implemented in the MONA software [3].

4. References

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