Magnetohydrodynamic and bubbles driving forces impact on dispersion and convection of alumina in the bath of an Hall-Héroult cell

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Abstract

The alumina concentration in the bath plays a fundamental role on cell operation. Local depletion may lead to an anode effect. A mathematical model describing the alumina convection-diffusion process in the bath coupled to the cell magneto-hydrodynamic (MHD) is presented. The relative importance of the velocity field and the alumina diffusion coefficient on the alumina concentration in the bath is discussed.

Introduction

The aluminum industry is continuously increasing the productivity of electrolysis cells by increasing the line current. In order to keep an acceptable anode current density, the anode length is almost systematically increased. As a result the central channel (distance between the anodes in the center of the cell) and the side channels (distance between the anodes to the side lining) are reduced. The channel geometry, Lorentz force field and bubbles have an important impact on the bath velocity. We will see that the velocity field plays a key role on the alumina distribution. In order to keep an acceptable energy input when increasing the current, the anode to cathode distance (ACD) is reduced as much as possible before reaching the Magneto-Hydrodynamic constraints. This means a further bath volume reduction. The increase of current imposes an increase of alumina feeding rate simultaneously with a reduction of bath volume. Therefore, the question of dissolution, diffusion and alumina transport becomes an important element for avoiding underfeeding leading to an increase of anode effects (AE) frequency. Alumina dissolution is a very complex phenomena in which the bath chemical composition, bath temperature, alumina temperature and alumina properties play an important role [1, 2, 3]. In this paper it is assumed that the dissolution is instantaneous when the alumina reaches the bath surface. The study concentrates on the diffusion and transport processes. The purpose of the study is to optimize the feeding quantities (feeding frequency) and the alumina feeders location.

Bath velocity field in presence of bubbles and Lorentz force field

The determination of the velocity field in presence of a great number of bubbles and Lorentz forces is by itself a complicated task that is out of the scope of this paper. The large number of bubbles is used to perform an average over the bath respecting specific discontinuities constraints at the interfaces. The equations used for the determination of the velocity fields in the metal and bath are given in reference [4]. In this paper we will assume that the velocity field is known and will discuss the diffusion-convection alumina equation.

Alumina dispersion coefficient

The diffusion-convection equation is well-known and given by:

$$\frac{\partial c}{\partial t} - div(\alpha \nabla c) + (v \mid \nabla c) = 0 \qquad \text{(Eq. 1)}$$

where
c is the alumina concentration,
α is the dispersion coefficient,
v is the velocity field.

The first term represents the local variation of alumina concentration over time, the second term the diffusion of alumina and the last term the transport (convection) of alumina by the bath velocity field. The only coefficient in the equation is the dispersion coefficient. One should mention that the diffusion coefficient of alumina in absence of bubbles was determined to be 2.0 0x10^{-9} m^2/s by Thonstad in reference [6]. Due to local turbulence in the bath mainly due to the bubbles, the diffusion coefficient is strongly increased and one speaks about dispersion. Equation (1) is therefore using a dispersion coefficient that is much bigger than the diffusion coefficient.

In our formulation, it is assumed that the alumina in flowing inside the bath under the feeders location and the alumina is leaving the bath as aluminum and oxygen. Therefore the following boundary conditions are considered:

- Alumina feeding under the surface of the feeders in an amount such that it satisfies Faraday's law for the current. We assume a constant current efficiency of 95% and 165 kA.
- An alumina concentration flux on the anodes with a coefficient β_1 such that the mass balance of O_2 (or CO_2) leaving at the anodes satisfies the alumina input.
- An alumina concentration flux at the cathode with a coefficient β_2 such that the mass balance of Al produced at the anodes satisfies the alumina input.
- No alumina flux elsewhere (no sludge formation, no alumina falling from any other place than the feeders,…).
- The initial alumina concentration is given.

This is expressed mathematically by:

- Under the feeder $\alpha \frac{\partial c}{\partial n} = F(t)$, where $F(t)$ is the feeding pattern. In this computation, it is chosen as a constant.

- On the anodes the boundary condition is $\alpha \frac{\partial c}{\partial n} + \beta_1 (j \mid n) = 0$, and on the cathode (bath-metal interface) $\alpha \frac{\partial c}{\partial n} + \beta_2 (j \mid n) = 0$.

- Elsewhere, a no flux boundary condition is imposed $\alpha \frac{\partial c}{\partial n} = 0$.

- The initial condition concentration is given by $c(x, t=0) = c_0(x)$.

Figure 1 illustrates the boundary conditions:

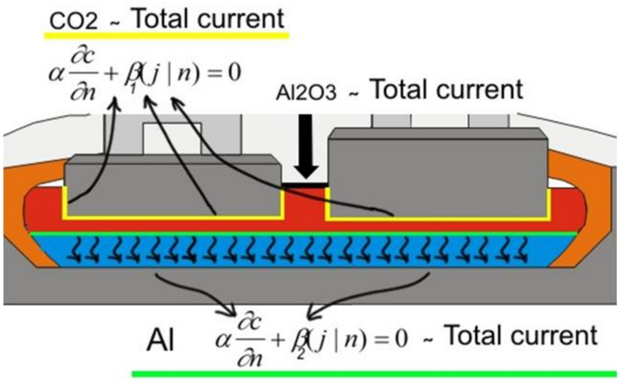


Figure 1: Boundary conditions for the alumina diffusion-convection equation in presence of alumina feeding and turbulent velocity field in the bath

In order to compute the alumina convection-diffusion, a full magneto-hydrodynamic calculation must be performed. This was done on a full three dimensional model of the cell. The metal deformation, the ledge shape, the metal and bath velocity fields were determined. Figure 2 shows the current density two centimeters under the anodes. All anodes were assumed to be at mid-life (we know it is never the case but it is the average over time). The bottom of the anodes was deformed according to the shape of the bath-metal interface. Some anodes were slightly higher in order to simulate a non-uniform anode current distribution.

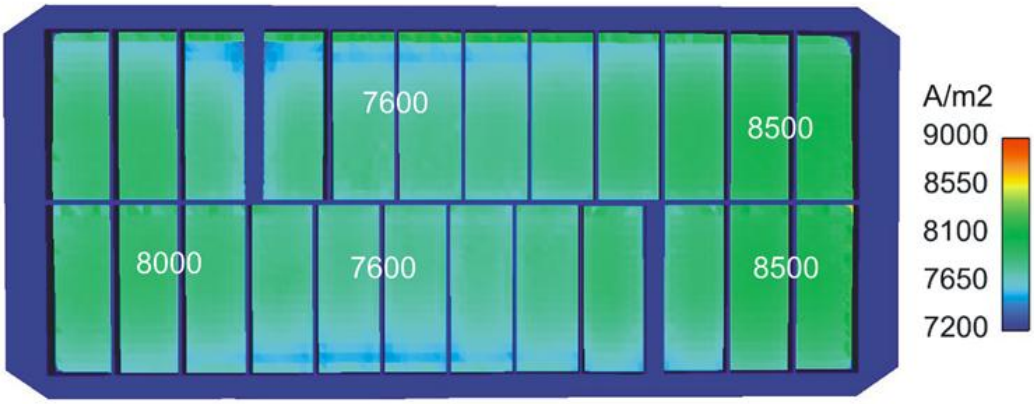
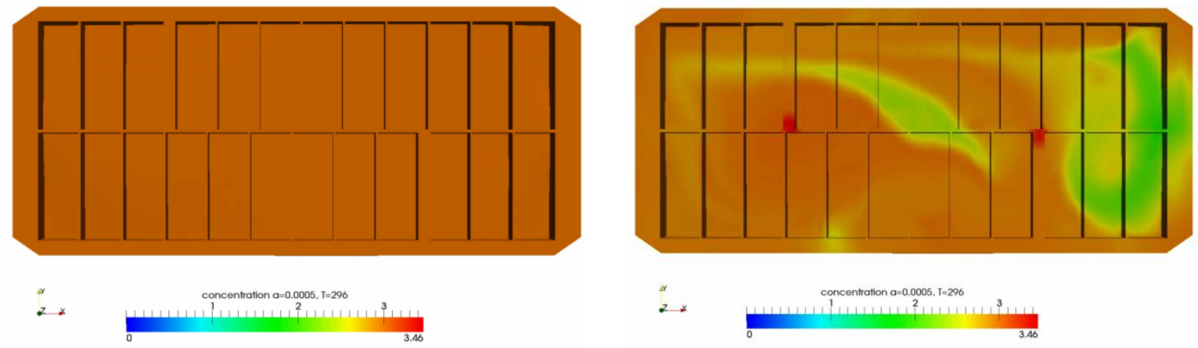


Figure 2: Current density 2 cm under the anodes

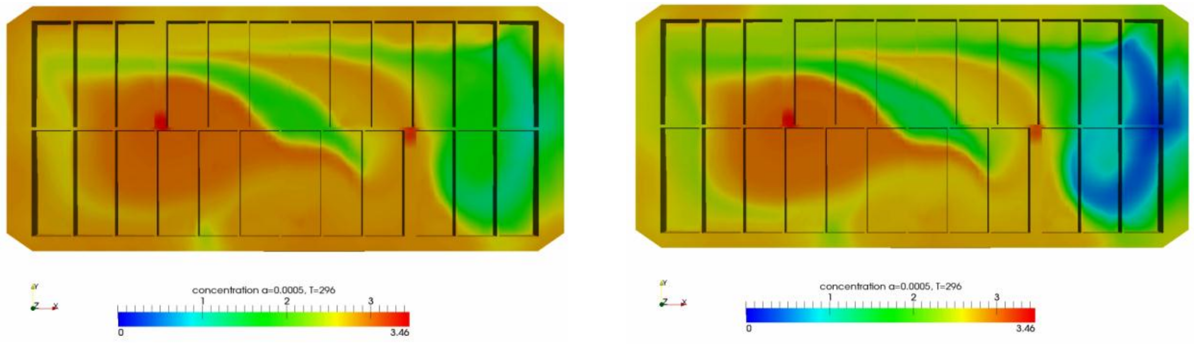
The asymmetrical current density situation must lead to an asymmetrical alumina concentration at stationary state. It is therefore an interesting case to study.

First the calculations were performed with a dispersion coefficient of 5.0×10^{-4} as suggested in [5].
Figure 3 shows the evolution of the alumina concentration in the cell starting from an homogeneous state with 3% alumina in the bath.



Time =0 second

Time =100 seconds



Time =200 seconds

Time =296 seconds

Figure 3: Alumina concentration evolution when starting with 3% alumina in the bath
Dispersion coefficient is 0.0005 m2/s. Velocity is non zero

After 296 seconds, the alumina concentration reaches 0% in the right hand side of the cell where the current density is maximal under the anodes. In fact an anode effect would have occurred earlier! As the feeding rate was kept constant and equal to the needed feed rate according to the total current, the cell should normally not reach the anode effect!

In the above calculation the electrolytic need for the alumina is fed and the velocity field helps at distributing the alumina. However, the dispersion coefficient is too small to compensate for the alumina need in the right hand side of the cell. We started to question the dispersion coefficient, the only parameter of the diffusion-convection equation. Based on fluid flow analysis, we suggested that the dispersion coefficient should be closed to $5.0x10^{-3}$, that is ten times bigger than initially used. In order to validate the coefficient, we decided to perform the following experience.

A cell was starved (no alumina feeding), the beam was blocked (no voltage fluctuations beside bath composition change). The voltage was recorded with a frequency of 1 Hertz (Figure 4). The cell reached the anode effect after 36 minutes. The best fit using all theoretical voltage curves (bubbles voltage, anode overvoltage, cathode overvoltage, ….) was applied on the measurements. As a result, the bath alumina concentration was determined at the start and at the end of the analysis. The time to reach the anode effect was 36 minutes.

```
 -----------------------------
    FCN        1.18342E-01
 -----------------------------
  1 ACD        0.44169E+01
          +-   0.17062E+00
    T          0.95900E+03
  2 CAL2O3     0.26448E+01
          +-   0.79423E-01
    ALF3       0.12200E+02
  3 ETA        0.92124E+02
          +-   0.57635E+01
  4 m_bath     0.22556E+04
          +-   0.11231E+03
    CAF2       0.60400E+01
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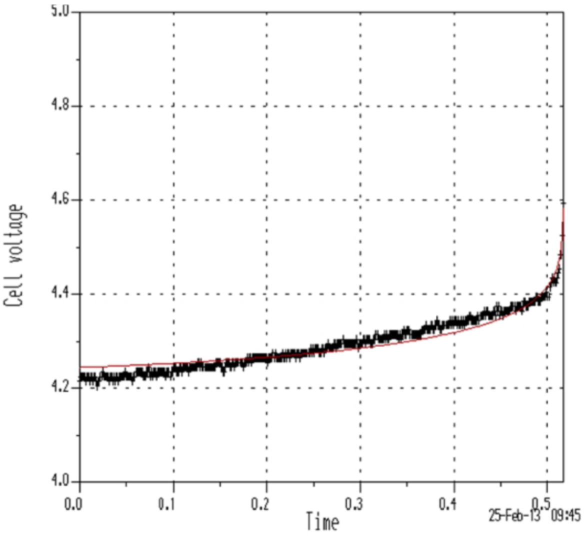


At time t=0, $C_{Al_2O_3}$=3.04%. AE after 36 minutes

Figure 4: Measured and fitted voltage as function of time when the feeding is stopped (120 kA cell)

The alumina concentration when the anode effect took place was determined to be 1.05 % (Figure 5).

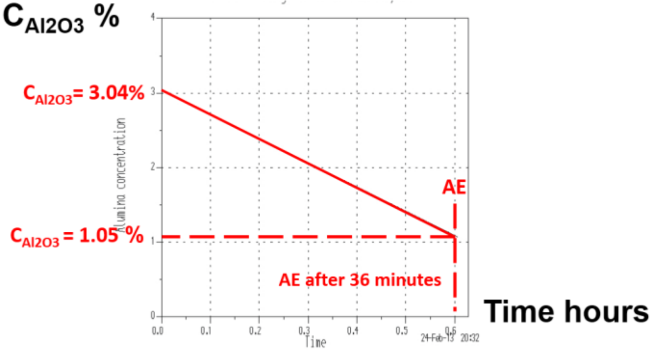


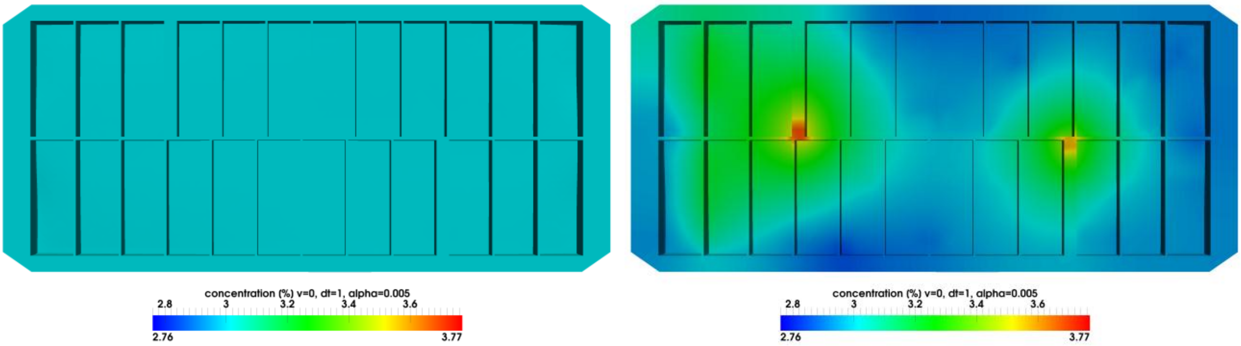
Figure 5: Alumina concentration at anode effect

The dispersion coefficient was determined in order to fit the three constraints. It happens to be that the dispersion coefficient of 5.0x10^{-3} gives reasonable results. This coefficient is also issued from the hydrodynamic theory, considering local turbulence due to bubbles.

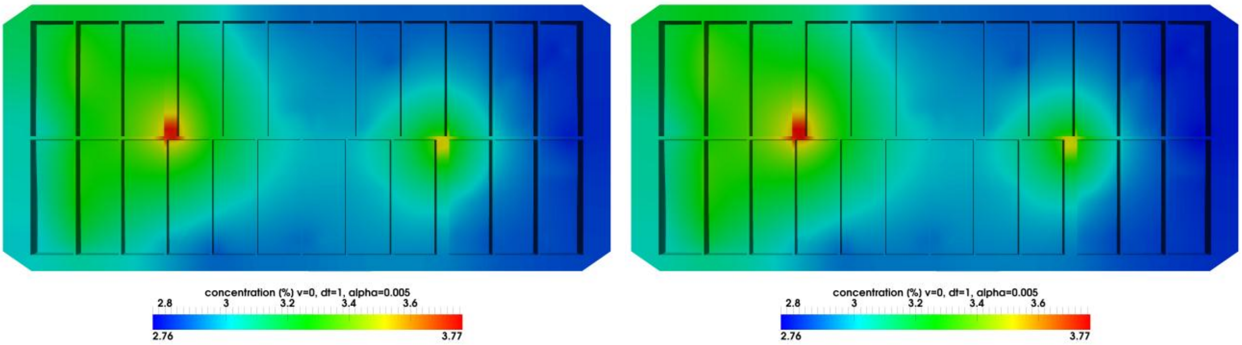
In fact the alumina does not really diffuse like heat in a solid media but is locally transported by the turbulence. This is the reason for speaking about dispersion. We will therefore use a dispersion coefficient of 5.0x10^{-3} in the next calculations.

Alumina concentration in the bath of one specific cell

The problem has been solved for an end to end 165 kA cell using two point feeders. The alumina flow rate under the feeders satisfies Faraday's law. As a stationary solution is presented, continuous feeding is assumed. The impact of dump feeding could easily be analyzed. Figures 6 shows the evolution of alumina concentration when the velocity is neglected (no convection). The concentration is shown 2 cm under the anodes. The two feeder locations appear clearly in the figure. The asymmetry of the diffusion pattern reflects the higher current density in the downstream side of the cell.



v=0, time = 0 v=0, time=600 s



v=0, time=2400 s v=0, time=3600 s

Figure 6: Alumina concentration evolution when starting with 3% alumina in the bath
Dispersion coefficient is 0.005 m2/s. Velocity is 0 m/s

After one hour, the stationary state is reached when no velocity field (no convection) is acting. The maximum difference in alumina concentration in the bath is 1% and it is typically 0.5% under the anodes. Obviously, the anodes leading the highest current show the lowest alumina concentration in the bath. The next calculations show the impact of the velocity field.

Figure 7 shows the velocity field generated by the bubbles and Lorentz force in the cell.

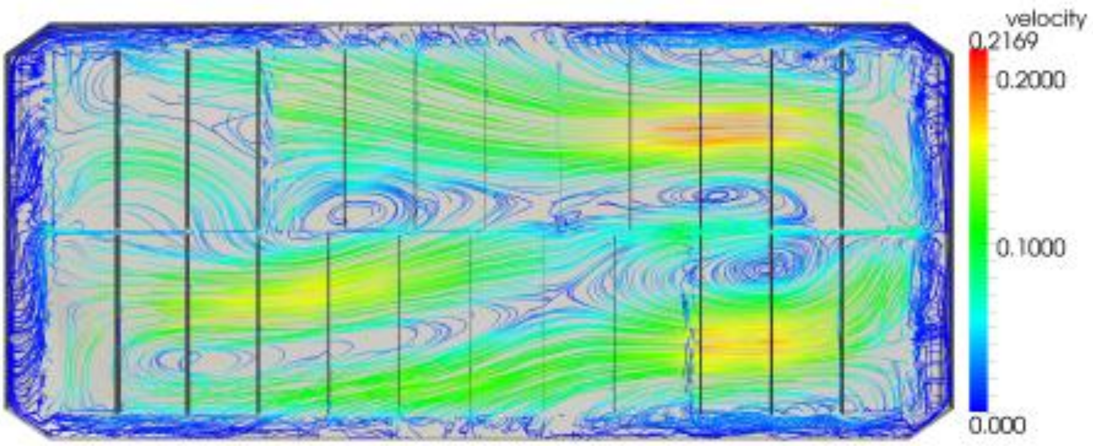
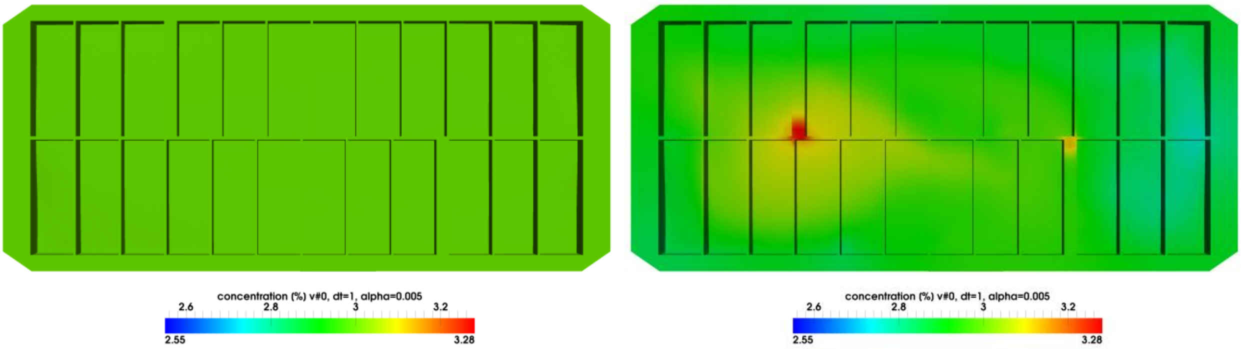


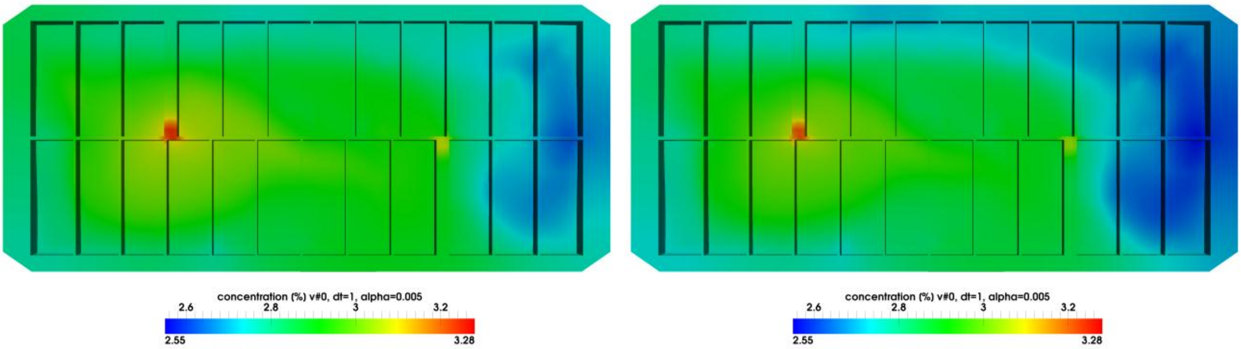
Figure 7: Velocity field in the bath of the cell

The impact of the velocity field on the evolution of alumina concentration in the bath is shown in figures 8. Initially the concentration is set to 3% in the whole liquid bath. The stationary state is reached after only 10 minutes, this is 6 times faster than in absence of convection. The maximum difference of alumina concentration is reduced by a factor two. The velocity plays a key role for homogenizing the alumina concentration in the bath and reduced the time to reach its location by a factor of 6.



v is non zero, time=0 s

v is non zero, time=240 s



v is non zero, time=480 s

v is non zero, time=600 s

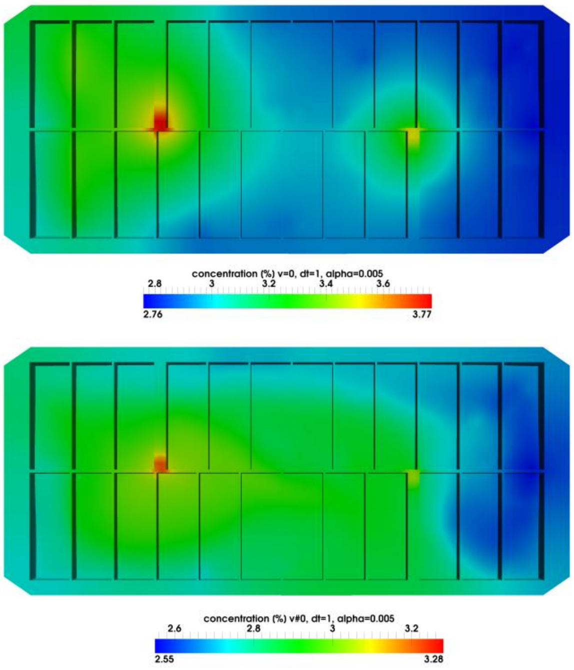
Figure 8: Alumina concentration evolution when starting with 3% alumina in the bath Dispersion coefficient is 0.005 m2/s. Velocity is non zero

Conclusion

A model for the velocity field in presence of MHD and bubbles has been developed. The velocity field has been used to determine the evolution of the alumina concentration using a non-stationary convection-diffusion model. This equation takes into account the feeding and the Faraday law at the anodes and cathode. The application to a specific end to end 165 kA cell using two point feeders demonstrates the following:

- The dispersion coefficient has been validated by measurements and is equal to 5.0X10^{-3} m^2/s.
- The alumina concentration can vary up to 0.5% in the bath, no more than 0.25% under the anodes when assuming constant alumina feed.
- The alumina distribution is significantly affected by the velocity field, which helps at homogenising the alumina.
- The velocity reduces the time needed to reach the stationary state by a factor of 6 when compared to dispersion only. It takes about 10 minutes to reach a stationary state.
- Figure 9 summarizes the impact of the velocity on the alumina concentration

Dispersion coefficient $\alpha = 0.005 m^2/s$



$v = 0$

Stationary state after 60 minutes
Max $\Delta_{Al_2O_3} = 1\%$

v is non zero

Stationary state after 10 minutes

Max $\Delta_{Al_2O_3} = 0.5\%$

Figure 9: Impact of velocity field on the alumina in the bath of some SØRAL cell

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