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PRODUCTION APPLICATION STUDY ON MAGNETO-HYDRO-DYNAMIC STABILITY OF A LARGE PREBAKED ANODE ALUMINUM REDUCTION CELL

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Abstract

The magneto-hydro-dynamic stability of an aluminum reduction cell has an important influence on aluminum electrolysis production. The paper introduces the research theory of magneto-hydro-dynamic stability of a cell and puts forward the concepts of “stationary state” and “transient state” of a reduction cell. A magneto-hydro-dynamic stability software is then used to calculate two different cell conditions. The calculated results prove to be consistent with the actual production, which confirms the model validity.

Introduction

An aluminum reduction pot consists of a carbon anode, a bath melt, a metal melt and a carbon cathode. The large DC passing through the aluminum busbar, the anode, the bath, the metal and the cathode etc. during aluminum reduction generates hundreds of Gauss strong magnetic field. This field interacts with the current in the metal to generate an electromagnetic force which accelerates the metal circulation in the pot. This results on one hand in an efficient way to dissolve alumina in the bath and then reduce it to aluminium. But on the other hand, it causes metal pad fluctuation, so that the current efficiency (CE) is reduced and the energy consumption must be increased in order to prevent excessive metal pad fluctuation. In severe cases, the metal can splash from the pot and cause accidents [1].

The studies of the conditions that generate metal pad fluctuation caused by the magnetic force in the pot are called magneto-hydro-dynamic (MHD) stability studies in the aluminum industry. With the development of large pot designs, the pot capacity gradually increases, so the MHD stability has become the core issue in the large pot design, as well as the important index reflecting the merits of pot design. Generally a pot having good MHD stability is characterized by better busbar arrangement, better magnetic field distribution, low voltage fluctuation noise, and better CE and power consumption index.

Therefore, MHD stability studies have practical significance in analyzing the various input conditions and physical parameters that are affecting the pot stability by performing mathematical simulation of the metal pad fluctuations affected by the pot design and process operation. Researchers have kept exploring and perfecting the calculation method of the MHD stability for years in the aluminum industry, yet it seems from the published literature that there are only few experts and scholars who can successfully solve the issue of MHD stability calculation.

This paper introduces the MHD stability theory of a pot, and establishes the 3-dimensional calculation model of MHD stability using pot dimensions and busbar arrangement of an actual pot. It also compares the calculations against observations in one particular smelter operating 340kA pots in China.

Magneto-hydro-dynamic stability theory

Definition of pot production states

The large prebaked anode aluminum reduction pot can be mathematically represented into two states under production conditions. In the “stationary state”, the pot is under non-disturbance conditions with stable current and without anode change, tapping, anode effect (AE) and breaking feeding. Such state is a kind of ideal state that never really occurs during actual production, since generally the pots are continuously disturbed by normal process operations. In the other “transient state”, the pot is under disturbance conditions with current fluctuation, anode change, tapping and breaking feeding which can not be prevented. In short, “stationary state” is a state without any temporal disturbances, and “transient state” is a state where temporal disturbances are present.

Mathematic definition of MHD stability of pot

For the “shallow water” approximation, the horizontal dimensions Lx and Ly are assumed to be much larger than the typical depth H, and the interface wave typical amplitude A is assumed to be small compared to the depth.

With the purpose to derive weakly nonlinear shallow layer approximation Boussinesq equations for the wave motion, the terms in the full three dimensional Navier-Stokes equations of motion need to be estimated. Nondimensional fluid flow equations (continuity, horizontal momentum and vertical momentum transport) are respectively [2,3,4,5]:

$$\partial_k u_k + \delta^{-1} \partial_{\bar{z}} w = 0 \qquad (1)$$

$$\partial_t u_j + u_k \partial_k u_j + \delta^{-1} w \partial_{\bar{z}} u_j = -\partial_j p + \mathrm{Re}^{-1}(\delta^{-2} \partial_{\bar{z}} \bar{v}_e \partial_{\bar{z}} u_j + \partial_k \bar{v}_e \partial_k u_j) + E f_j \qquad (2)$$

$$\partial_t w + u_k \partial_k w + \delta^{-1} w \partial_{\bar{z}} w = -\delta^{-1} \partial_{\bar{z}} p + \mathrm{Re}^{-1}(\delta^{-2} \partial_{\bar{z}} \bar{v}_e \partial_{\bar{z}} w + \partial_k \bar{v}_e \partial_k w) + E f_z - \delta^{-1} \qquad (3)$$

When the depth averaging procedure is applied to the horizontal momentum equations (2) we obtain:

$$\begin{aligned} &\partial_t \hat{u}_j + \hat{u}_k \partial_k \hat{u}_j = \\ &\quad -\partial_j p(\overline{H}_0) - \varepsilon \partial_j \varsigma - \mu \hat{u}_j + \mathrm{Re}^{-1} \partial_k \overline{v}_e \partial_k \hat{u}_{0j} \\ &\quad + E \hat{f}_j - \tfrac{1}{2} \delta E \overline{H}_i \partial_j f_{0z} + O(\varepsilon^2, \delta^2, \varepsilon\delta) \end{aligned} \tag{4}$$

The momentum (4) and continuity (1) equations for the two fluid layers can be combined in a single nonlinear wave equation for the interface ζ(x,y,t).

$$\begin{aligned} &\varepsilon \left\langle \frac{\rho}{\overline{H}} \right\rangle \partial_{tt} \varsigma + \varepsilon \left\langle \frac{\mu\rho}{\overline{H}} \right\rangle \partial_t \varsigma + \varepsilon \langle \rho \rangle \partial_{jj} \varsigma = \\ &\quad E \left\langle \partial_j \hat{f}_j \right\rangle - \delta E \left\langle \tfrac{1}{2} \overline{H} \partial_{jj} \hat{f}_z \right\rangle \\ &\quad -\varepsilon \left\langle \frac{\rho}{\overline{H}} \partial_{tj} (\varsigma u_{jo}) + \frac{\mu\rho}{\overline{H}} \partial_j (\varsigma u_{jo}) \right\rangle - \left\langle \rho \partial_j (\hat{u}_k \partial_k \hat{u}_j) \right\rangle \end{aligned} \tag{5}$$

Equation (5) is used for the numerical solution of the interface wave development with coupling to the horizontal circulation obtained from the numerical solution of (4).

The equations are by definition transient but, depending on the initial conditions and in the absence of further perturbations, could converge to a "stationary state" where the solution is no longer changing when time passes. That "stationary state" solution can be characterized with high or low "permanent" metal pad deformation and by high or low horizontal circulation flow.

Physical definition of pot MHD stability

From the above arguments, it can be concluded that the study on the pot MHD stability should have two objectives: 1. quickly study the "stationary state" solution trying to identify characteristics of a stable design; 2. generate a perturbation and carry a much longer fully non-linear "transient state" analysis to really check if the cell design is predicted to return to its "stationary state" after such a perturbation.

In summary, the issue of pot MHD stability can be defined as follows: disturbances happen on the pot under normal production conditions, or in a special conditions such as when some anodes are removed. The pot can then return to its original state or transit to the new stable state after a certain time. If it does, the pot is regarded as stable under such normal production state or special conditions, otherwise it is regarded as unstable.

Calculated results under normal conditions

Calculation model of pot and busbar layout

Using the MHD-Valdis [2] computer software, the relevant parameters regarding pot and busbar layout are input according to a particular form, thus obtaining a model of 340KA pot and busbar layout in an aluminum smelter. The resulting geometry setup of the model is shown in figure 1.

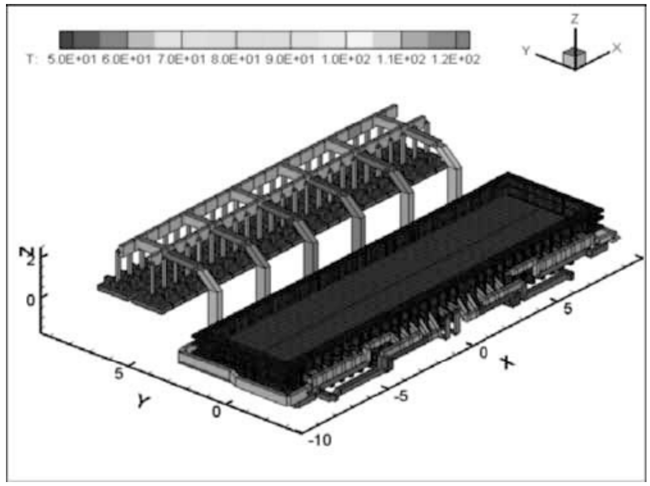

Figure 1. Model of a 340 kA pot including busbar layout

Initial "stationary" state

Before solving in full non-linear transient mode, it is advantageous to solve first the "stationary" state in order to be able to quickly screen out less promising designs, based on design criteria such as the maximum vertical component of the magnetic field (B_Z), the maximum horizontal current component in the metal pad (J_y), the maximum metal pad velocity and the maximum deformation of the metal surface per example.

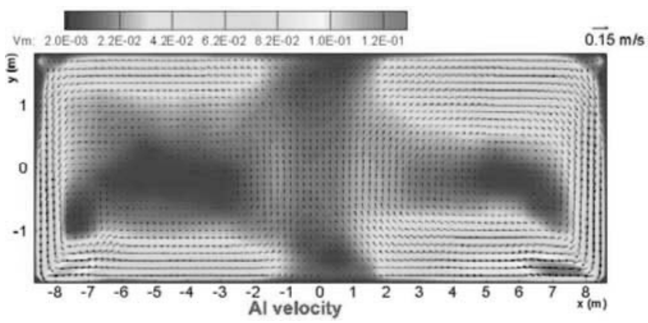

Figure 2. Initial "stationary" state metal flow under ACD = 0.045m

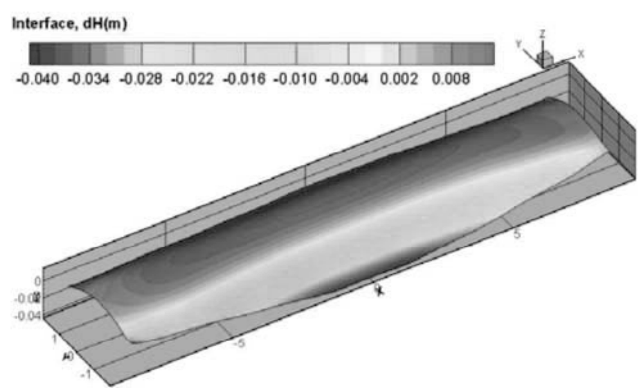

Figure 3. Initial "stationary" state metal surface under ACD = 0.045m

Voltage fluctuation result chart

In figures 2 and 3, the initial "stationary" state of the 340 kA pot looks quite acceptable, with a low velocity symmetric recirculation flow pattern (maximum of 12 cm/s) and a symmetric and acceptable maximum surface deformation (less than 5 cm). Unfortunately, solving only the initial "stationary" state is not sufficient to know if the pot will be stable in operation; for that, the full non-linear transient solution must be solved as well.

The pot voltage fluctuation after an initial perturbation is calculated under different anode-cathode distances (ACD) including 0.055 m, 0.05 m, 0.045 m and 0.040 m. The results are presented in figure 4 for three variables, including the corner anode ACD on the downstream duct end, the corner anode ACD on the upstream tap end, and the total pot voltage. The pot voltage fluctuation resulting from metal fluctuation is observed to see whether it becomes stable as time progresses.

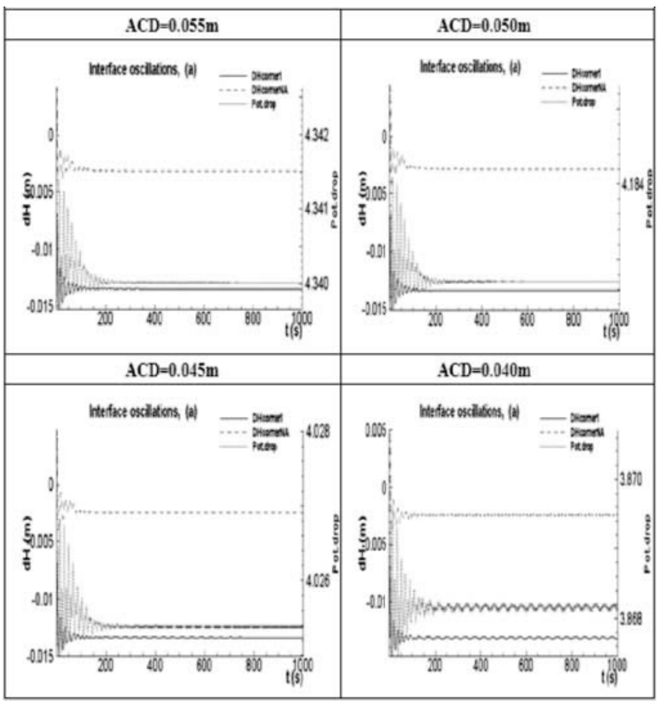

Figure 4. Voltage fluctuation chart under ACD between 0.040 m and 0.055 m

It shows that the pot can remain stable as the ACD reduces to 0.040 m, but if the voltage fluctuation increases, the conditions reflected in production are that the noise increases.

In order to make distinction and comparison, the voltage fluctuation under an ACD of 0.035 m is calculated (figure 5).

It shows that as time progresses, the metal fluctuation increases gradually under the corner anode on the downstream duct end under an ACD of 0.035 m. This causes voltage fluctuation of the total pot, which may generate short-circuit risk. Therefore this illustrates that the pot is not able to remain stable under an ACD of 0.035 m.

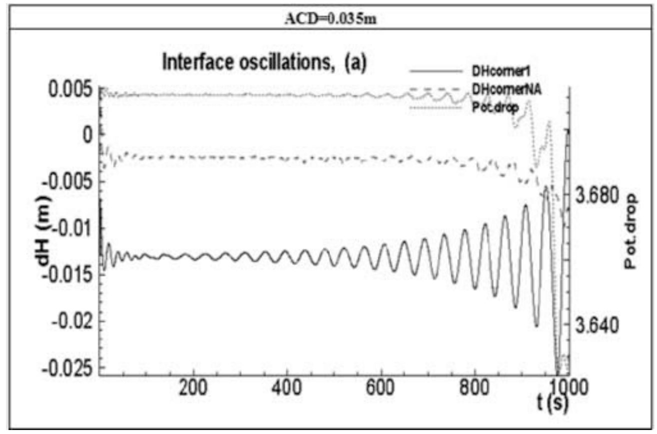

Figure 5. Voltage fluctuation chart under ACD = 0.035 m

Metal surface fluctuation chart

As time goes on, under an ACD of 0.035 m, the metal surface fluctuation chart is as follows:

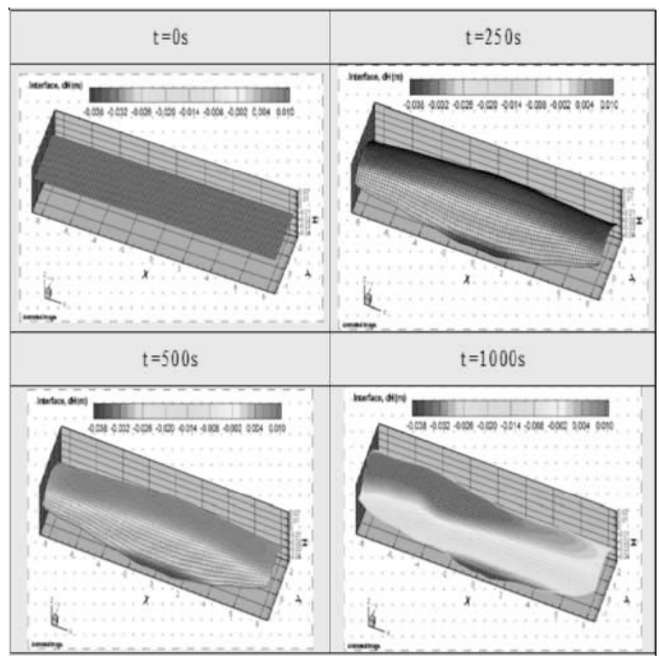

Figure 6. Metal surface fluctuation chart under ACD = 0.035 m

It shows clearly that the metal surface fluctuation is broadly out of control and that the metal could eventually splash out of the pot to cause an accident.

Final "stationary" state

Notice that if the pot is predicted to be stable, the "transient" state triggered by the perturbation will "converge" back into a "stationary" state that will by definition no longer evolve as time passes.

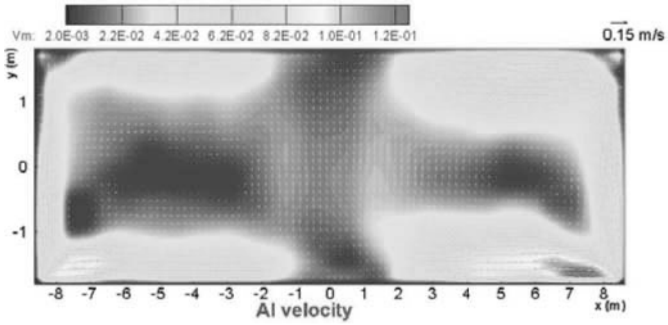

Figure 7. Final "stationary" state metal flow ACD = 0.045 m

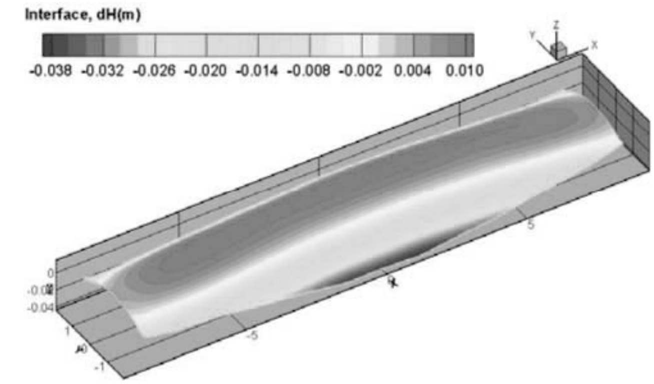

Figure 8. Final "stationary" state metal surface ACD = 0.045 m

Comparing figures 2 and 3 with figures 7 and 8 shows that after being affected by the perturbation, the pot is predicted to settle back into the initial "stationary" state which may not be systematically the case.

Calculated results with some anodes removed

The premise of calculation of MHD under special conditions is that the two corner anodes on downstream duct end are removed. In this case, we obverse whether the voltage fluctuation and the metal surface fluctuation stay in control as time progresses.

Initial "stationary" state

The "stationary" state in the context of this special anode removed conditions assumes that those anodes have been permanently removed.

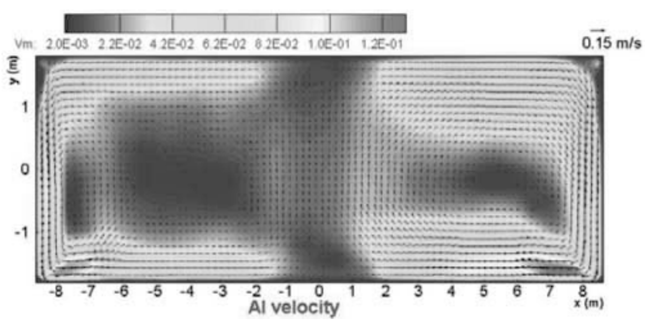

Figure 9. Initial "stationary" state metal flow ACD = 0.045 m, some anodes removed

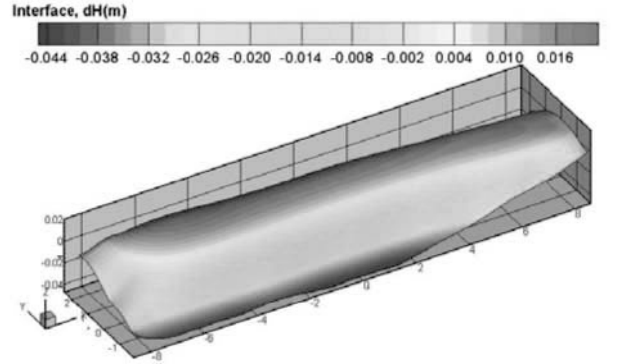

Figure 10. Initial "stationary" state metal surface ACD = 0.045 m, some anodes removed

Comparing figures 2 and 3 with figures 9 and 10, the initial "stationary" state metal flow is not significantly affected by the "permanent" removal of the two anodes, but the initial "stationary" state metal surface is significantly affected as the metal surface deformation is no longer symmetric and the maximum deformation has increased to 6 cm.

Voltage fluctuation result chart

It is clear that removing anodes is not good for the pot MHD stability. But again, it is only by running the full non-linear transient analysis that will we know if the pot will remain stable under those special conditions. Under an ACD of 0.045 m, with two corner anodes removed on the downstream duct end, the pot voltage fluctuation chart is as follows:

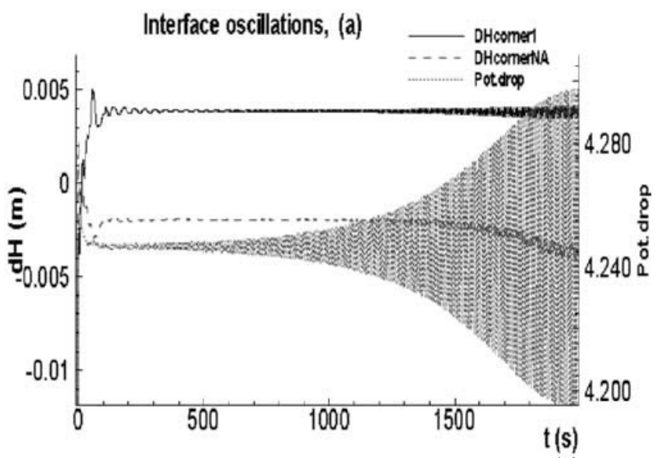

Figure 11. Voltage fluctuation chart with anode removal for ACD = 0.045 m

With the anode removal, as time progresses the pot voltage fluctuation increases gradually. It then shows that the pot design is not very robust, and that the MHD stability in anode change conditions is worse than in normal conditions.

Metal surface fluctuation chart

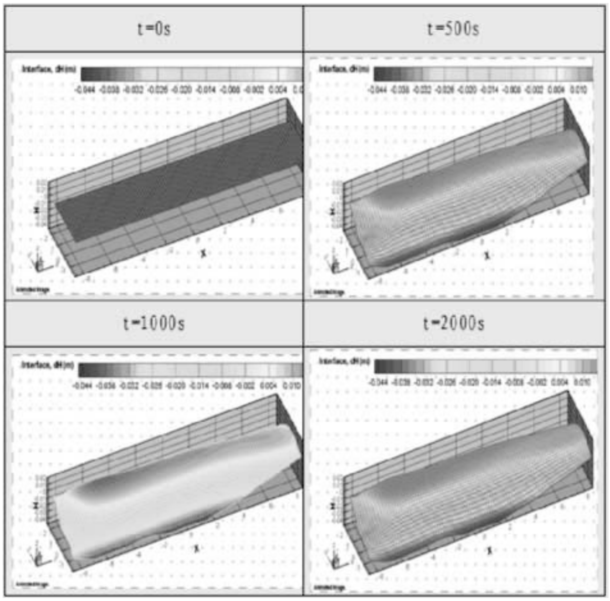

Figure 12. Metal surface fluctuation chart with anode removal for ACD = 0.045 m

Figure 12 shows that under an ACD of 0.045 m, with two corner anodes removed, the pot is predicted to experience significant metal pad fluctuation. In this case, the conditions reflected on the control system of the master computer are that the pot voltage noise has increased significantly.

Conditions observed in production

This kind of pot has been in production for years, and the conditions observed in production are summarized as follows:

1) The pot voltage was minimized to about 4.0 V.

2) Without anode change, metal tapping and AE, the pot is in good condition all day without voltage fluctuation.

3) As an anode changed, generally within 8 hours, the pot stability has deteriorated as high noise and heavy voltage fluctuation are observed. Even though the voltage is increased appropriately, it is hard to control the conditions.

4) Since the pot has an anode change every day, the pot voltage fluctuation has a cyclic occurrence synchronised with the cycle of anode change time. This means that quite often the process technical conditions are hard to stabilize.

Comparison of calculated results vs conditions observed in production

The conditions observed in production are compared with the calculated results of pot MHD stability and the analysis is as follows item by item:

1) Under normal conditions, the calculated pot voltage can be minimized to 3.87 V while the noise is high.

2) Under normal conditions, if the ACD is 0.040 m or more, the pot can remain stable.

3) The pot is sensitive to the anode change under an ACD of 0.045 m. An instability period can then occur after an anode change unless the ACD is more than 0.045 m, and hence the power consumption needs to be increased.

4) Statistics show that generally the full current passes through new anodes 8 hours after they are put in the pot. The pot is then in special anode change conditions for one-third of the time each day. Due to cyclic occurrence of anode change every day, the pot suffers an impact within 8 hours every day, which will certainly cause the successive unbalanced energy.

Conclusions

From the above mentioned calculation and analysis, it can be concluded as follows:

1) As the pot capacity increases, it will become more and more important to study the MHD stability which has the value of directing design and operating conditions.

2) For the design of MHD stability, the normal conditions and the special anode change conditions of the pot must be calculated fully.

3) The calculation model of MHD stability in this paper is reasonable, calculated results and conditions observed in production match pretty closely, thus confirming the value of the MHD-Valdis software for the purpose of production applications.

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