PRODUCTION APPLICATION STUDY ON MAGNETO-HYDRO-DYNAMIC STABILITY OF 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

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

The study on 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 reduction pot, 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 the 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 has practical significance, analysing the various input conditions and physical parameters that are affecting the pot stability performing mathematical simulation of the metal pad fluctuation affected by the pot design and process operation. Researchers have kept exploring and perfecting the calculation method of the MHD stability for years in 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 pot, and establishes the 3-dimensional calculation model of MHD stability of pot as per actual pot dimension and busbar arrangement, as well as compares the calculation against observations in one certain 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 2 states under production conditions. One is called "stationary state", namely 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 occur during actual production, generally pots are continuously disturbed by normal process operations. The other one is called "transient state", namely 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 relative to the depth.

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

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

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

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

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

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

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).

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

The equation (5) is used for the numerical solution of the interface waves 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 pass. 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

It concludes that from the above-mentioned arguments the study on the pot MHD stability should have 2 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 "transiant state" analysis to really check if the cell design is predicted to return on its "stationary state" after such a perturbation.

In summary, the issue of pot MHD stability can be defined as follow: disturbances happen on the pot under normal production conditions or in some special conditions like when some anodes are removed, the pot can then return the its original state or transit to the new stable state after 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 it according to a particular form, thus obtains a model of 340KA pot and busbar layout in a aluminum smelter. The resulting geometry setup of the model is shown in figure 1.

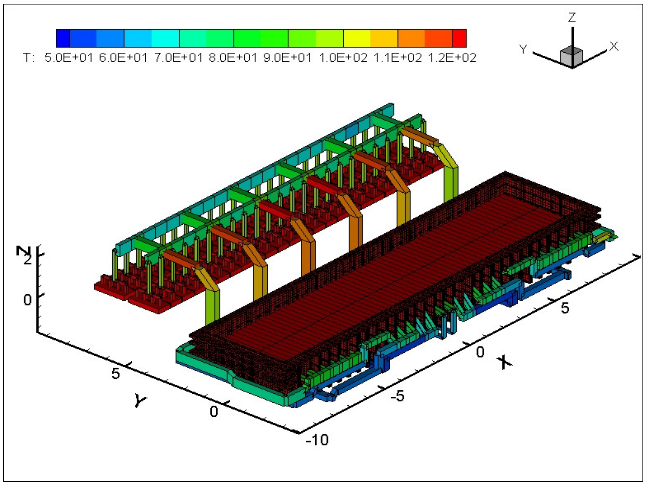

Figure 1. Model of 340 kA pot including busbar layout

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 screen out quickly less promising design based on some design criteria like the maximum vertical component of the magnetic field (Bz), maximum horizontal current component in the metal pad (Jy), maximum metal pad velocity and maximum deformation of the metal surface per example.

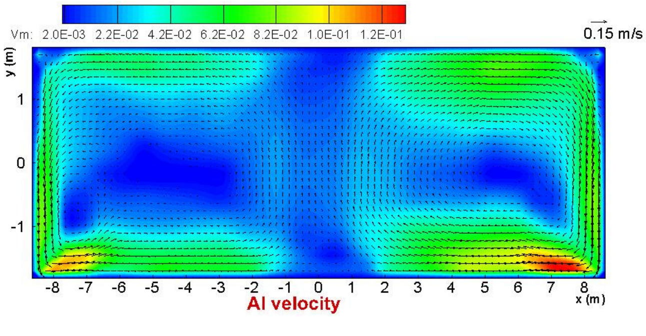

Figure 2. Initial "stationary" state metal flow under ACD = 0.045m

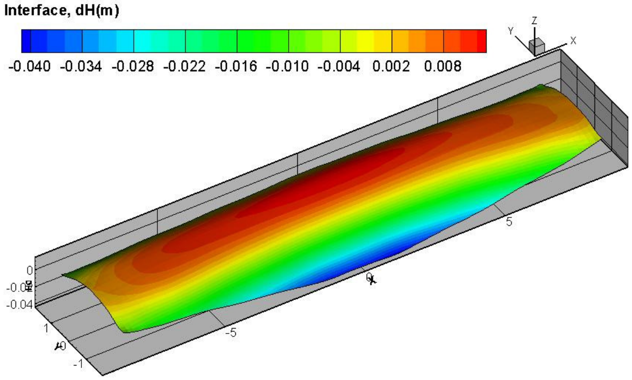

Figure 3. Initial "stationary" state metal surface under ACD = 0.045m

Voltage fluctuation result chart

As we can see 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 enough to know if the pot will be stable in operation, for that the full non-linear transient solution must be solve as well.

The pot voltage fluctuation after an initial perturbation is calculated under different anode-cathode distances (ACD) including 0.055m, 0.05m, 0.045m and 0.040m. The results are presented in figure 2 for 3 variables including corner anode ACD on the downstream duct end, corner anode ACD on the upstream at tapping end the total pot voltage are selected. Pot voltage fluctuation resulted from metal fluctuation is observed for that whether it becomes stable as time goes on.

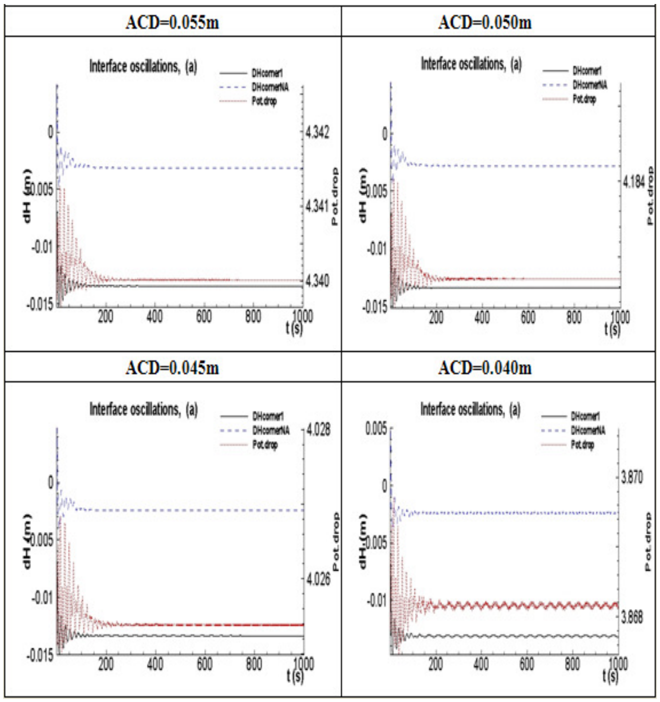

Figure 4. Voltage fluctuation chart under ACD between 0.040m and 0.055m

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

In order to make distinction and comparison, the voltage fluctuation under ACD 0.035m is calculated.

It shows that as time goes on the metal fluctuation increases gradually under the corner anode on the downstream duct end under ACD 0.035m, thus brings out the much voltage fluctuation of the total pot, which may generate short-circuit risk. Therefore this illustrates the pot is impossible to remain stable under ACD 0.035m.

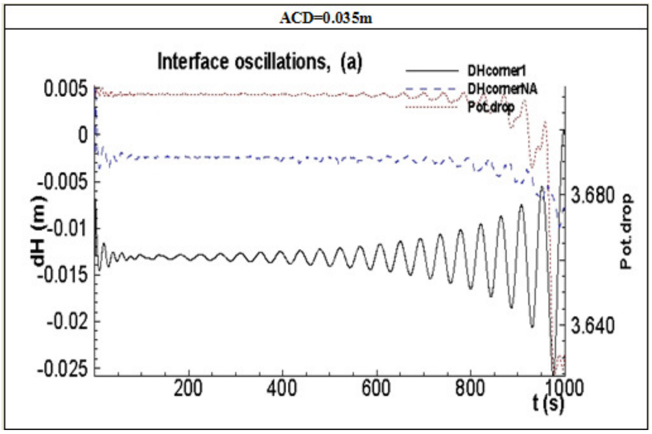

Figure 5. Voltage fluctuation chart under ACD = 0.035m

Metal surface fluctuation chart

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

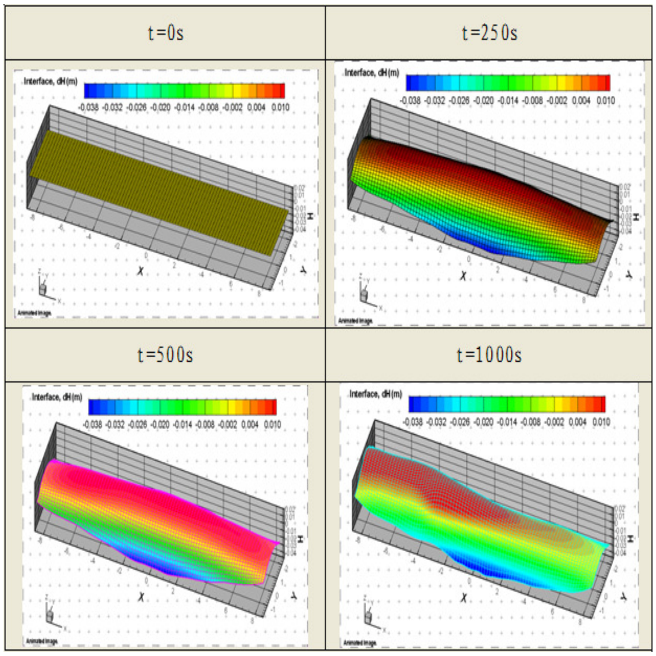

Figure 6. Metal surface fluctuation chart under ACD = 0.035m

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

Final “stationary” state

Notice that if the pot is predicted to be stable, “transient” state triggered by the perturbation will “converged” back into a “stationary” state that will by definition no longer evolves as time pass.

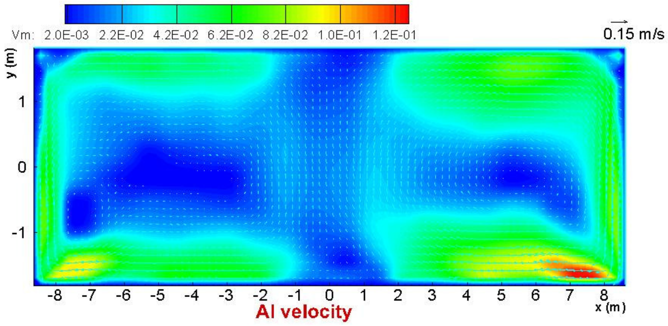

Figure 7. Final "stationary" state metal flow under ACD = 0.045m

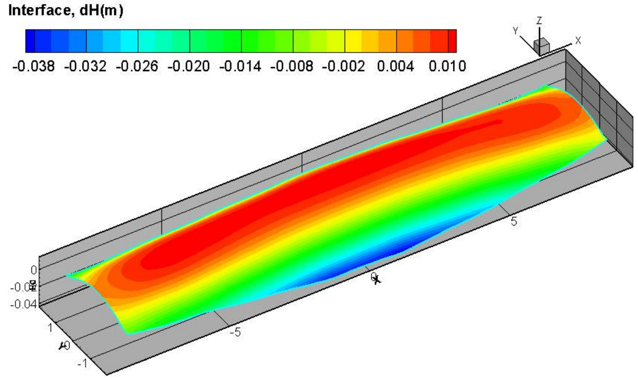

Figure 8. Final "stationary" state metal surface under ACD = 0.045m

As we can see comparing figures 2 and 3 with figures 7 and 8, 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 2 corner anodes on downstream duct end are removed, in this case obverses whether the voltage fluctuation and metal surface fluctuation is in control as time goes on.

Initial "stationary" state

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

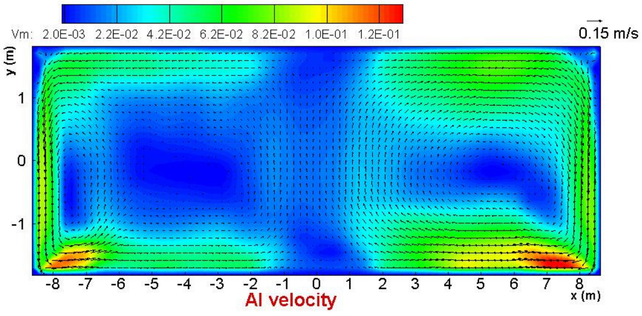

Figure 9. Initial "stationary" state metal flow under ACD = 0.045m

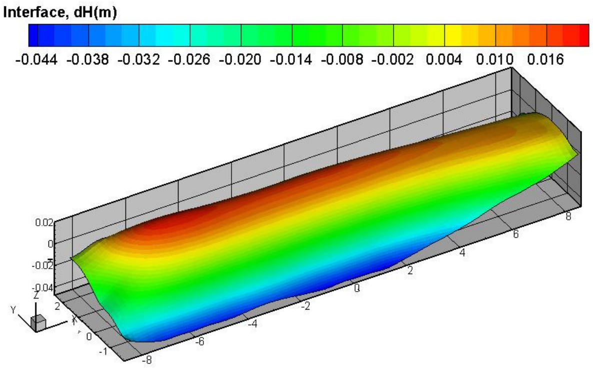

Figure 10. Initial "stationary" state metal surface under ACD = 0.045m

As we can see comparing figures 2 and 3 with figures 9 and 10, the initial "stationary" state metal flow is not much affected by the "permanent" removal of the 2 anodes but the initial "stationary" state metal surface is quite affected as the metal surface deformation is no longer symmetric and the maximum deformation has increased to 6 cm.

Voltage fluctuation result chart

So clearly removing anodes is not good for the pot MHD stability but again only by running the full non-linear transient analysis will we know if the pot will remain stable under those special conditions. Under ACD 0.045 m, with 2 corner anodes removal on downstream duct end, the pot voltage fluctuation chart is as follows:

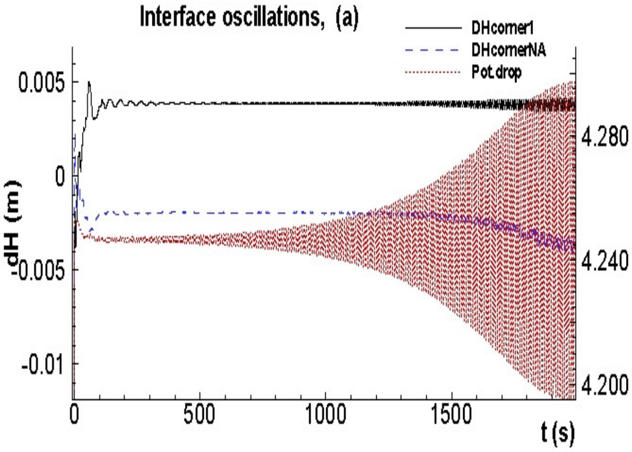

Figure 11. Voltage fluctuation chart with anode removal of ACD=0.045m

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

Metal surface fluctuation chart

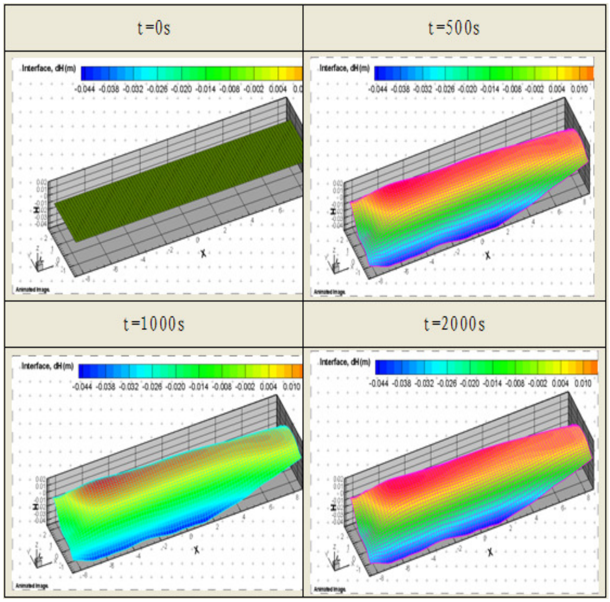

Figure 12. Metal surface fluctuation chart with anode removal of ACD= 0.045m

It shows that: under ACD 0.045m, with 2 corner anode removed, the pot is predicted experience significant metal pad fluctuation, in this case the conditions reflected on the control system of master computer is that the pot voltage noise has increases significantly.

Conditions observed in production

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

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

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

3) Once the pot has anode changed, generally within 8 hours it has bad stability, high noise and heavy voltage fluctuation, in this case even through the voltage is increased appropriately, it is hard to control the conditions.

4) Since the pot has anode change every day, the pot voltage fluctuation is a cyclic occurrence in sync with the cyclic of anode change time, thus brings out that the process technical conditions are hard to be stabilized quite often.

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 ACD is 0.040 m or more, the pot can remain stable.

3) The pot is sensitive to the anode change under ACD 0.045 m, so the pot can have instability period after anode change unless the ACD is more than 0.045 m, and hence the power consumption need to be increased.

4) As per statistics, generally the full current passes through new anodes 8 hours after they are put in the pot, so the pot is in special anode change conditions within one-third of the time of all 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 conclude 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 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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