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Effect of gas bubble on cell voltage oscillations based on equivalent circuit simulation in aluminum electrolysis cell

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Abstract: A method to investigate the effect of gas bubble on cell voltage oscillations was established. The whole aluminum electrolysis cell was treated as a resistance circuit, and the dynamic simulation of the cell equivalent circuit was modeled with Matlab/Simulink simulation software. The time-series signals of cell voltage and anode current were obtained under different bubble conditions, and analyzed by spectral and statistical analysis methods. The simulation results show that higher bubble release frequency has a significant effect on the cell voltage oscillations. When the bubble coverage of one anode block exceeds 80%, the cell voltage may exceed its normal fluctuation amplitude. The simulation also proves that the anode effect detected by computer in actual production is mainly the whole cell anode effect.

Key words: aluminum electrolysis; equivalent circuit; gas bubble; cell voltage; anode effect

1 Introduction

Pre-baked anode aluminum electrolysis cell is the main equipment in the production of aluminum. It is actually an electrochemical cell with multi-anode and single cathode. In the cell, alumina dissolves in the melt cryolite between anode and cathode. When anode current density is in normal conditions, the following reaction mainly occurs at the carbon block immersed in the electrolyte:

$$Al_2O_3+1.5C(s)=2Al(l)+1.5CO_2(g) \qquad (1)$$

In this reaction, CO_2 is produced. Because the producing bubbles underneath the anode block cannot be discharged in time, bubbles are partly attached to the underneath surface of the anode, and also some mix with the electrolyte. Due to the poor electrical conductivity of gas, all of these bubbles will increase the resistance of the electrolytic circuit [1,2]. The variation in the cell resistance will cause the change of current distribution and cell voltage fluctuation. The extra cell voltage drop due to gas bubbles may be in the range of 0.15−0.35 V [3], which has a significant loss of energy through Ohmic heating.

Bubble covering the surface of the anode carbon block not only increases the resistance between anode and cathode, but also reduces anode contact area with the electrolyte, which will influence the electrochemical reaction on the anode surface. At the same time, it is the main driver for alumina mixing and bath flow [4]. So, the gas bubbles play an important role in cell operation.

The aluminum reduction cell is a highly corrosive closed system with high temperature. It is difficult to directly observe and determine the gas generation and release processes, so researches on the anode gas are mainly conducted through laboratory study and physical-mathematical model [4−6]. These researches investigated the bubble creation, detachment, transport and its impact on the cell voltage based on small size electrolysis cells or room temperature hydrodynamic models. The gas bubble behavior depends on the anode current density, anode shape and inclination, and electrolysis parameters [7,8]. Lots of research results [1,9] show that the gas coverage fraction on the anode surface is 30%−60%. In addition, the bubbles release periodically from the anode surface, which will disturb the electrolyte and affect liquid aluminum fluctuation. The release frequency of the bubbles is 0.3−3 Hz [10,11]. The relation between cell voltage fluctuation and bubble noise was also

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investigated [3,12], showing that bubbles are subjected to the frequency and the amplitude of the voltage oscillations. From these studies, we have known about the formation, growth, and motion of gas bubbles to a certain extent.

However, most of these studies are based on a single anode electric field [1,2,4,8]. It is different to the real cell, which contains a multi-anode and a single cathode. When the gas bubbles under the anode bottom surface come to change, the anode current will redistribute. The authors have not found published studies on the numerical model of anode gas bubbles concerning the multi-anode phenomenon in aluminum cell.

The main idea of this work is to simplify the aluminum electrolytic cell as an electrical resistance circuit model, and build the simulation model with Matlab/Simulink simulation software. In this work, it is assumed that the liquid aluminum fluctuation waveform is a sine wave, and bubbles release from the anode surface periodically. Considering the change of alumina concentration and anodic overvoltage, the effect of different bubble release frequencies and coverage fraction on the current distribution and cell voltage is studied by statistical and spectral analysis methods.

2 Description of cell physical model

In the production of aluminum, constant DC current feeds the anode rod from the busbar, flows through the anode carbon block, electrolyte, liquid aluminum, cathode block, and finally outflows from the cathode bars. If the cell can be seen as a resistance circuit, wherein the anode rod, cathode block and cathode bars can be regarded as fixed resistors. Since the liquid aluminum has a very low electrical resistivity, its resistance can be neglected. Furthermore, there are some variable resistors between anode and cathode. Figure 1 shows the equivalent circuit schematic diagram of part aluminum electrolysis cell.

So, the cell voltage (U) can be represented as

$$U=E_{re}+R_{an}I+R_{ov}I+R_{acd}I+R_{bu}I+R_{ca}I+R_{other}I \tag{2}$$

where E_{re} is the reaction electromotive force and R_{other} is the resistance of cathode bar.

The anode is consumed as the current flows through, so its resistance gradually decreases. Moreover, the anode is also an electric conductor. The anode resistance decreases very slowly within a short time. In order to simplify the calculation model, this study assumes that the anode is consumed uniformly. That is to say, the resistance is uniformly reduced in a pole changing period. In this work, it is assumed that the anode consumption period is 28 d according to the actual production process.

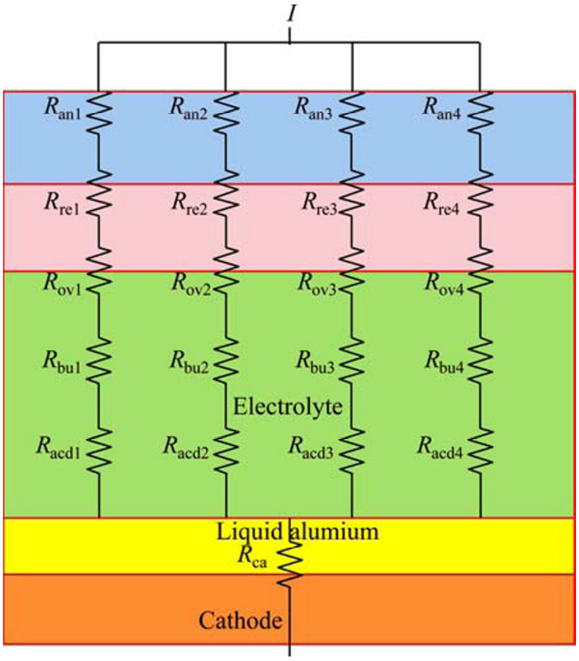

Fig. 1 Equivalent circuit schematic diagram of part aluminum electrolysis cell (I—DC; R_{an}—Electric resistance of anode block; R_{re}—Electrochemical reaction resistance; R_{ov}—Anode surface overvoltage resistance; R_{bu}—Bubble resistance; R_{acd}—Electrolytic resistance; R_{ca}—Cathode resistance. It is assumed that the cell reaction occurs in the anode surface, and produces R_{re} and R_{ov}, gas bubbles mainly adhere to the anode surface

In normal production the main reaction (1) occurs in the cell. According to the Nernst's equation, the reaction electromotive force E_{re} can be given as

$$E_{re}=E^0-\frac{RT}{zF}\ln\left(\frac{p_{CO_2}^{1.5}\alpha_{Al}^2}{\alpha_{Al_2O_3}\alpha_C^{1.5}}\right) \tag{3}$$

where $p_{CO_2}^{1.5}$ is partial pressure of CO_2; α_{Al}, $\alpha_{Al_2O_3}$ and α_C are the aluminum, alumina and carbon activity, respectively; R is mole gas constant; F is Faraday's number; T is reaction temperature in Kelvin; E^0 is the standard potential, which is a function of temperature. In the reaction (1), E^0 is [13]

$$E^0=-1.8984+5.725\times10^{-4}T \tag{4}$$

z is number of electrons involved in a reaction, here z=12.

Assuming that $p_{CO_2}=1$, $\alpha_{Al}=1$, $\alpha_C=1$, then,

$$E_{re}=E^0+\frac{2RT}{zF}\ln\alpha_{Al_2O_3} \tag{5}$$

In the bath, the activity of Al_2O_3 can be expressed as [14]

$$\alpha_{Al_2O_3}=\left[\frac{\omega_{Al_2O_3}}{\omega_{Al_2O_3(sat)}}\right]^{2.77} \tag{6}$$