PURIFICAÇÃO DE ELETRÓLITO ALCALINO DE PRODUTOS DE REAÇÃO DISSOLVIDOS DURANTE A OPERAÇÃO DA FONTE DE CORRENTE QUÍMICA DE AR E ALUMÍNIO

PURIFICATION OF ALKALINE ELECTROLYTE FROM DISSOLVED REACTION PRODUCTS DURING WORK OF THE AIR-ALUMINUM CHEMICAL CURRENT SOURCE

ОЧИСТКА ЩЕЛОЧНОГО ЭЛЕКТРОЛИТА ОТ РАСТВОРЕННЫХ ПРОДУКТОВ РЕАКЦИИ В ПРОЦЕССЕ РАБОТЫ ВОЗДУШНО-АЛЮМИНИЕВОГО ХИМИЧЕСКОГО ИСТОЧНИКА ТОКА

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RESUMO

A relevância do artigo se baseia no fato de que a criação de usinas de energia elétrica com fontes de corrente química de ar e alumínio está na fase de desenvolvimento e teste de amostras e protótipos. O objetivo do artigo é calcular as dimensões do circuito eletrolítico e do cristalizador. Foram realizados estudos experimentais da cinética do processo de decomposição de soluções de aluminato de potássio na faixa de temperatura e composição correspondentes às condições operacionais de usinas de energia elétrica com fontes de corrente química de ar e alumínio para diversos fins. O artigo apresenta os resultados da aplicação de vários métodos de purificação do eletrólito alcalino a partir de produtos de reação dissolvidos formados durante a operação de uma fonte de corrente química de ar e alumínio. Os parâmetros cinéticos da decomposição de soluções de aluminato são determinados experimentalmente, dependendo da temperatura, da concentração de alumínio dissolvido, da concentração de hidróxido de alumínio da semente e do tamanho da superfície da semente. As dimensões dos sistemas de purificação de eletrólitos de produtos de reação dissolvidos - o circuito de eletrólitos e o cristalizador – foram calculadas, o que aumentou significativamente o tempo de operação contínua de usinas com base na fonte de corrente química de ar e alumínio. Foi mostrado que, para uma usina de 100 W, o volume do cristalizador é de 1,3 L com uma concentração de sementes de 20% em peso. A massa de água consumida durante a operação da usina por 6 horas é de 1,4 kg.

Palavras-chave: *Instalação eletroquímica, purificação de eletrólitos, soluções supersaturadas de aluminato, cristalização, processo de decomposição da solução.*

ABSTRACT

The relevance of the article is based on the fact that the state of work on the creation of power sources (PS) with AA chemical current sources (CCS) is at the stage of development and testing of prototypes. The purpose of this article is to calculate dimensions of the electrolyte circuit and the crystallizer. There were experimental studies of the decomposition kinetics of the process solutions of potassium aluminate in the range of temperatures and compositions corresponding to operating conditions with PS AA CCS for various purposes. This study presents the results of applying various methods of cleaning an alkaline electrolyte from dissolved reaction products formed during the operation of an air-aluminum (AA) chemical current source (CCS). The kinetic parameters of decomposition of aluminate solutions were experimentally determined, depending on temperature, the concentration of dissolved aluminum, concentration of initial aluminum hydroxide and the size of the first surface. The dimensions of the electrolyte purification systems from dissolved reaction products — electrolyte circuit and crystallizer — were calculated, which significantly increased the time continuous operation of power

sources (PS) based on AA CCS. It was demonstrated that for a 100 W power supply, the crystallizer volume should be 1.3 l with initial concentration of 20 % of mass. The mass of water consumed during the operation of the PS for 6 hours is 1.4 kg.

Keywords: *Electrochemical installation, electrolyte purification, supersaturated aluminate solutions, crystallization, solution decomposition process.*

АННОТАЦИЯ

Актуальность статьи заключается в том, что состояние работ по созданию энергоустановок (ЭУ) с ВА химическими источниками тока (ХИТ) находятся на стадии разработки и испытания макетных и опытных образцов. Цель статьи – провести расчет габаритов электролитного контура и кристаллизатора. Были проведены экспериментальные исследования кинетики процесса декомпозиции растворов алюминатов калия в интервале температур и составов, соответствующим условиям работы ЭУ с ВА ХИТ различного назначения. В работе приведены результаты применения различных методов очистки щелочного электролита от растворённых продуктов реакции, образующихся при работе воздушно-алюминиевого (ВА) химического источника тока (ХИТ). Экспериментально определены кинетические параметры процесса декомпозиции алюминатных растворов, в зависимости от температуры, концентрации растворенного алюминия, концентрации затравочного гидроксида алюминия и величины затравочной поверхности. Проведены расчеты габаритов систем очистки электролита от растворенных продуктов реакции – электролитного контура и кристаллизатора, позволяющих существенно увеличить время непрерывной работы энергоустановок (ЭУ) на основе ВА ХИТ. Показано, что для ЭУ мощностью 100 Вт объем кристаллизатора составляет 1,3 л при концентрации затравки 20 мас.%. Масса воды, расходуемой при работе ЭУ в течение 6 часов, равна 1,4 кг.

Ключевые слова: *Электрохимическая установка, очищение электролита, пересыщенные алюминатные растворы, кристаллизация, процесс декомпозиции растворов.*

1. INTRODUCTION

One of the most effective and promising electrochemical systems is oxygen- (air-) aluminum pair (O_2 / Al or AA) with aqueous electrolytes. Currently, the state of work on the creation of power sources (PS) with AA chemical current sources (CCS) is at the stage of development and testing of prototypes. They have high specific energy consumption (up to $700 \text{ W} \cdot \text{h} / \text{kg}$) and a unique set of working properties: long-term storage before work and during pauses, complete explosion and fire safety, the absence of toxic components and work products, which determines the possibility of widespread use in various equipment (Skvortsov *et al.*, 2016; Skvortsov *et al.*, 2018).

An additional positive quality of the considered CCS is the possibility of using and processing the resulting reaction products. The resulting aluminum hydroxide can be a feedstock for aluminum production. In this case, the system can be considered as mechanically rechargeable with charge and discharge processes separated in space and time. Therefore, in terms of the energy, cost, technological, and operational characteristics, the oxygen-aluminum electrochemical pair is one of the most effective

and promising combinations. The schematic diagram of AA CCS with alkaline electrolyte is shown in Figure 1. The main reactions and the place of their occurrence are shown there.

As we can see from the scheme, the main products of the AA CCS reaction are soluble aluminates and solid aluminum hydroxide $Al(OH)_3$. Currently, the causes of the functional failure of the AA CCS and the parameters affecting the resource of PS based on them are determined. It was demonstrated that the time of one operation cycle is limited by the process of passivation of the working surface of the anode with a film consisting of reaction products. We have developed several methods that can significantly increase the time of continuous operation of power units with AA CCS. The main ones are the use of corrosion inhibitors and anode depassivators in an electrochemical reaction (Pushkin *et al.*, 2018; Farmakovskaya *et al.*, 2018a; Farmakovskaya *et al.*, 2018b; Okorokova *et al.*, 2015a; Egan *et al.*, 2013; Li and Bjerrum, 2002; Doche *et al.*, 1997; Okorokova *et al.*, 2015b; Okorokova *et al.*, 2010; Okorokova *et al.*, 2011; Pushkin, 2014; Karonik *et al.*, 1988; Shao *et al.*, 2002; Soler *et al.*, 2007).

In addition, an analysis of the operability of AA CCS and PS based on them also showed that

in regimes with high current densities, the time of continuous operation and the life of the PS are limited both by passivation of the aluminum anode and destruction of the gas diffusion cathode by the formed dissolved and solid reaction products. It is possible to achieve an improvement in characteristics of the cell and increase in the operating life of electric actuator if conditions are created that reduce the concentration of reaction products in the electrolyte (Skvortsov *et al.*, 2000; Akbarov *et al.*, 2018; Burkov *et al.*, 2018; Gavryushin *et al.*, 2018).

The easiest way to clean the electrolyte from dissolved aluminates is the decomposition of supersaturated aluminate solutions by crystallization on seed aluminum hydroxide, followed by removal of solid $\text{Al}(\text{OH})_3$.

Nonetheless, the available information on the kinetic parameters of the crystallization process and currently developed devices and methods for calculating such crystallizers relate to the processes of industrial production of aluminum and solutions of sodium aluminates. Thus, the development of a methodology for calculating a system for purifying an electrolyte from dissolved aluminates and crystals of aluminum hydroxide as applied to AA CCS is a very urgent task. In this study, we present the results of studies on the application of various methods of purification of alkaline electrolyte from dissolved reaction products formed during the operation of AA CCS. The kinetic parameters of the decomposition of aluminate solutions are experimentally determined, depending on temperature, the concentration of dissolved aluminum, the concentration of initial aluminum hydroxide and the size of the surface. The dimensions of electrolyte purification systems from dissolved reaction products — the electrolyte circuit and the crystallizer — were calculated, which made it possible to significantly increase the continuous operation time of the PS based on AA CCS.

2. MATERIALS AND METHODS

As was mentioned, to ensure long-term operation of a power source with high and stable characteristics, it is necessary to conduct continuous or periodic cleaning of the electrolyte from dissolved reaction products.

A decrease in the concentration of aluminum in the electrolyte supersaturated with aluminates can also occur during natural crystallization. Nonetheless, due to the tendency of alkaline aluminate solutions to high supersaturations, this process either does not develop at all or proceeds

at an insufficient rate.

The composition of aluminate solutions can be characterized by the concentration of alkali, aluminum, and aluminum hydroxide expressed in mass %, g/l or mol/l. While, the widely used characteristic of the studied solutions is the supersaturation value for aluminum, determined by three main values: absolute supersaturation ΔC , relative supersaturation d and degree of supersaturation p , which are respectively equal to (Equations 1-3). Where C — is the concentration of aluminum in the solution, C_p — is the equilibrium concentration of aluminum.

In some cases, to characterize aluminate solutions, the values of alkaline pH and acid N modules representing molar ratios were used (Equations 4-5).

The features and behavior of aluminate solutions, in particular, the possibility of high supersaturation, stability, and delay of the decomposition process, reflect the patterns inherent in both true and colloidal systems. Thus, there are several different theories of the nature of aluminate solutions — colloidal, saline and mixed.

The salt theory, which treats aluminate solutions as ionic systems consisting of complex aluminate ions, is the most widely used. Aluminate solutions with a degree of supersaturation not exceeding $p = 0.8$ are characterized by six-fold coordination, leading to the formation of anions $\text{Al}(\text{OH})_6^{3-}$. An increase in the degree of supersaturation promotes the polymerization of ions according to the scheme (Equation 6).

With ion dehydration $\text{Al}(\text{OH})_4^-$ asymmetric oxyanions formed $\text{AlO}(\text{OH})_2^-$ polymerize due to hydrogen bonds. It is also possible to have dehydration of concentrated solutions according to the scheme (Equation 7).

Usually, in solutions with alkali concentration of more than 10 mass% and a degree of supersaturation of more than one, the process of ion polymerization also occurs. $\text{Al}(\text{OH})_4^-$. While, the most stable polymer groups are those that, with varying degrees of polymerization, do not change the sign and number of charges. This condition is satisfied in the case of combining ions $\text{Al}(\text{OH})_4^-$ into dimers, trimers, and ultimately into polymers. Thus, the formation of polymer compounds of aluminum ions can be as follows (Equation 8) or in general form (Equation 9).

This polymerization scheme takes into account the possible association of aluminum ions by forming bridges $-\text{Al}-\text{O}-\text{Al}-$. Additional confirmation of the course of polymerization of

anions $Al(OH)_4^- \rightleftharpoons AlO_2^- + 2H_2O$ is provided by the fact that when a certain concentration of aluminum is reached, all hydroxyl ions will be bound into these polymers. Nonetheless, a much larger amount of aluminum can be dissolved in such solutions, for which it is necessary to have free OH⁻ ions, the formation of which is possible as a result of the polymerization of aluminum anions according to Equation (9).

In the absence of strong decomposition initiators (solid phases, impurities, additives), aluminate solutions are quite stable and can stay in a metastable state for a long time. The polymerization process in this case, in this case, is balanced by the depolymerization process. For decomposition of an aluminate solution, it is necessary that the polymerization process ends with polycondensation – the release of a solid phase $Al(OH)_3$. Therefore, the course of the decomposition process in supersaturated aluminate solutions is determined by many factors, one of which is in which concentration range it occurs

A stable state of solution corresponds to concentrations less than or equal to equilibrium, and its crystallization without changing the state is impossible. The metastable range can be divided into two zones. The first one is between the equilibrium concentration and the concentration below which spontaneous crystallization is practically impossible, but possible using seed crystals. The second zone corresponds to concentrations at which spontaneous formation of crystals is possible, but, as a rule, crystallization does not occur immediately, but after a certain period of time, called the induction time (period).

The zone of the labile state of supersaturated aluminate solution is characterized by the fact that crystallization in it occurs instantly. For a complete understanding of the behavior of aluminate solutions formed during the operation of AA CCS and the course of the formation of solid reaction products in them, it was necessary to determine the boundaries of the metastable and labile zones of the state of solutions depending on alkali concentration and temperature.

We have chosen a method based on measuring the time of induction of spontaneous crystallization of solution with varying degrees of supersaturation. It was believed that the concentration of solutions that have an induction time tending to infinity corresponds to the first zone of the metastable region. The concentration of solutions with finite induction time corresponds to the second zone of metastability.

The induction time of the self-decomposition process, tending to zero, have solutions located in the labile region of the state. Nonetheless, the determination of true limiting supersaturations by this method is fraught with serious difficulties, consisting of the difficulty of accurate experimental measurement of extremely small values of induction periods. Thus, it is practically considered that if the time before the start of the crystallization process does not exceed one minute, the solution is in a labile state. Experiments were done for three alkali concentrations of 12, 16 and 20 mass% in the temperature range from 303 to 353 K. The experimental data are presented in Figures 2-4.

Based on the obtained data, the influence of temperature on the position of the boundaries of metastable and labile regions of the state of studied solutions was established (Figures 5-6).

Figure 5 demonstrates the absolute amount of aluminum that can be dissolved in an alkali solution corresponding to the working concentration of the electrolyte (20 mass%), and Figure 6 shows the real degrees of supersaturation that can be attained in one or another area of the state of the studied supersaturated aluminate solutions. The obtained results indicate that an increase in the concentration of alkali and, accordingly, the amount of hydroxide ions, leads to an increase in concentration of dissolved aluminum.

Nonetheless, the width of the metastable region has not changed. The relative size of the metastable region (Figure 6), in this case, decreases significantly. The obtained temperature dependences (Figure 5) demonstrate that with increasing temperature the metastable region narrows and, accordingly, the stability of aluminate solutions decreases, which, apparently, is a consequence of an increase in the rate of ion diffusion $Al(OH)_4^-$ accelerating the processes of polymerization and polycondensation.

Considering the abovementioned, we came to the conclusion that in the PS based on AA CCS it is necessary to carry out the forced decomposition of the electrolyte, in which supersaturated aluminate solutions crystallize on specially introduced seed crystals either in the electrolyte circuit or in a special device — the crystallizer according to the reaction (Equation 10).

For calculation of the dimensions of electrolyte circuit and crystallizer, we made experimental studies of the kinetics of decomposition of potassium aluminate solutions in

the temperature and composition range corresponding to the operating conditions of PS with AA CCS for various purposes and obtained data on the rates of this process depending on various factors. We studied solutions with a potassium alkali concentration of 12-22 mass% in the temperature range 293-333 K.

As initiating crystals, specially prepared or industrial aluminum hydroxide was used. The specific surface of the seed crystals was calculated based on the measurement of the particle size distribution of initiating aluminum hydroxide. Then, we proceeded from the following considerations that if particles are assumed to be spherical and identical in size, then their specific surface is equal to (Equation 11). Where r is the density of seed; d_1 is particle diameter of the seed.

3. RESULTS AND DISCUSSION:

As it was shown by the differential particle size distribution curves (Figure 7), the aluminum hydroxide used for the seed was a polydisperse powder, the specific surface of which was determined as the sum of the specific surfaces of the particles in the entire size range (Equation 12). Where N_1 – is a fraction of particles of diameter d_i in the measured sample.

The total seed surface in solution was (Equation 13). Where C_s – is the concentration of seed.

Since the decomposition rate constant is directly proportional to the seed surface, the linear growth constant of crystals, $k_{\log}$, was calculated from the slope of the straight line $k_{\log} = f(S)$, and then $k_{\log}$ (Equation 14). Where $K_v = 3a/b$ – is coefficient of matching the volume of powder particles with their surface; a , b – volumetric and surface form factor; for particles with a diameter of 2 to 20 μm , the coefficient K_v is estimated at 2.9.

The rate constants of the crystallization process of aluminum hydroxide at various temperatures were used to calculate the activation energy of this process according to the Arrhenius equation (15). Where E_a – is the activation energy of the decomposition process.

The crystallization process of aluminum hydroxide is characterized by the energy of activation equal to 54 ± 2 kJ/mol and does not depend on the composition of aluminate solution and the type of seed aluminum hydroxide.

Kinetic curves of the decomposition process of studied solutions, showing the dependence of

the processing speed on various factors are shown in Figures 8 and 9. The effect of alkali concentration on the decomposition of supersaturated aluminate solutions is shown in Figure 8, and the effect of temperature is shown in Figure 9. As we can see from the above data, an increase in alkali concentration and temperature leads to a decrease in the stability of aluminate solutions and an increase in the rate of their decomposition.

A typical kinetic dependence is illustrating the effect of the concentration of dissolved aluminum on the decomposition rate shown in Figure 10. It is non-linear and, regardless of other parameters, is described by a second-order kinetic equation (16):

where $k_{\log}$ – is the deposition rate constant; C and C_{eq} are the current and equilibrium aluminum concentrations, respectively.

Processing the obtained experimental data using a derived equation shows that the crystallization rate constant depends on the amount of seed (Figure 11) and, accordingly, the seed surface (Figure 12).

The studies of decomposition processes allowed us to determine the main parameters of the PS cleaning units – the electrolyte circuit and the crystallizer – and to maintain the optimal electrolyte composition at the input of the AA battery. The optimal parameters of the electrolyte circuit were estimated based on obtained values of decomposition rates. The time interval necessary for the crystallization process to take place was calculated by the formula (Equation 17). Where $-dC/dt$ – is the crystallization rate. ΔC_{Al} is the increase in the concentration of dissolved aluminum in electrolyte, which is equal to (Equation 18). Where C_{Al}^1 , C_{Al}^2 – are respectively, the concentration of aluminum at the input and output of the battery; M_{Al} – second consumption of aluminum; Q_{el} – electrolyte consumption through the battery.

The time required for decomposition should be provided by corresponding lengths of the electrolyte path in the circulation circuit and its speed (Equation 19). Where n – is the number of contour sections in which crystallization occurs; l_i , W_i – are respectively, the length and velocity of the electrolyte flow in these areas. Estimates performed according to formulas 17-19 and experiments carried out on PS prototypes showed that at medium work capacities and high decomposition rates corresponding to high concentrations of dissolved aluminum, the crystallization process could occur in the

electrolyte circulation circuit.

To reduce the concentration of dissolved aluminum, it is possible to increase the amount of seed in the electrolyte, which will inevitably lead to a significant increase in energy costs for pumping the electrolyte and decrease the resource and reliability of the operation of PS units, therefore, in some cases it is necessary to intensify the process of electrolyte purification. As we mentioned above, it is possible to use a crystallizer, in which it is possible to create the required concentrations of the seed. Then, the required dimensions of the simplest crystallizer can be calculated using Equations (20) and (21). Where t_{cr} – is the time of the electrolyte stays in a crystallizer, L_{cr} – is the length of the crystallizer; W_{el} is the electrolyte flow rate in the crystallizer.

The volume of the crystallizer can be determined by the formula (Equation 22).

A schematic diagram of a continuous submersible crystallizer is demonstrated in Figure 13.

4. CONCLUSIONS:

The boundaries of metastable and labile regions of the state of supersaturated aluminate solutions were determined on model solutions corresponding to working concentrations of the primary electrolytes of AA CCS.

The experiments conducted for three KOH alkali concentrations of 12, 16, and 20 mass % in the temperature range from 303 to 353 K allowed us to determine the absolute amount of aluminum that can be dissolved in alkali solution corresponding to the working electrolyte concentration (20 wt%), as well as real degrees of supersaturation that can be achieved in a particular area of existence of studied supersaturated aluminate solutions. The obtained results indicate that an increase in the concentration of alkali and, accordingly, the amount of hydroxide ions, leads to an increase in the concentration of dissolved aluminum.

Nonetheless, the width of the metastable region is practically unchanged, and the relative size of the metastable region is significantly reduced. The obtained temperature dependences show that with increasing temperature the metastable region narrows and, accordingly, the stability of aluminate solutions decreases, which, apparently, is a consequence of an increase in the rate of ion diffusion $Al(OH)_4^-$ accelerating processes of polymerization and polycondensation.

On model solutions, the kinetic parameters of decomposition of aluminate solutions were experimentally established, in relation to the composition of the solutions obtained during the operation of AA CCS in various modes, depending on temperature, the concentration of dissolved aluminum, concentration of seed aluminum hydroxide and the seed surface. As seed crystals, we used specially prepared or industrial aluminum hydroxide with known particle size distribution. Based on differential particle size distribution curves, the total seed surface in solution was calculated.

For solutions with an alkali concentration of 12-22 mass% in the temperature range of 293-333 K, it was demonstrated that an increase in alkalinity and temperature of solutions with the same degree of supersaturation increases the decomposition rate. The dependence of decomposition rate on aluminum concentration is nonlinear and is described by a second- order kinetic equation. The crystallization rate constant depends on the amount of seed and, accordingly, the seed surface. Based on the values of the rate constants of the crystallization of $Al(OH)_3$ at various temperatures, the activation energy of this process was calculated, which is 54 ± 2 kJ / mol and it does not depend on the composition of the aluminate solution and the type of seed aluminum hydroxide.

We made calculations on the dimensions of electrolyte purification systems from dissolved reaction products – electrolyte circuit and crystallizer. Experiments were done on PS prototypes, and they demonstrated that at medium operating powers and high decomposition rates corresponding to high concentrations of dissolved aluminum ($p = 1.5$), the crystallization process takes place in the electrolyte circulation circuit.

In order to reduce concentration of dissolved aluminum, it is possible to increase the amount of seed in electrolyte, which inevitably leads to a significant increase in energy costs for pumping the electrolyte and a decrease in the resource and reliability of operation of PS units, therefore, in some cases, to intensify the process of cleaning electrolyte, it is necessary to use a special device – a crystallizer, in which It is possible to create the required seed concentration.

Since the decomposition rate depends on temperature, the concentration of alkali and aluminum, and the amount of seed, the choice of the optimal design and operation of the mold is also largely determined by characteristics and operating conditions of the PS. Thus, to determine

the minimum mass and size of the mold, multi-parameter optimization should be done taking into account the given characteristics.

Evaluation calculations have demonstrated that for a 100 W power supply, the crystallizer volume should be 1.3 l at a seed concentration of 20 mass%. The mass of water consumed during the operation of the PS for 6 hours is 1.4 kg.

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$$\Delta C = C - C_p \quad (\text{Eq. 1})$$

$$d = \Delta C / C_p \quad (\text{Eq. 2})$$

$$d = \Delta C / C_p \quad (\text{Eq. 3})$$

$$\alpha = n(K_2O) / n(Al_2O_3) \quad (\text{Eq. 4})$$

$$N = n(Al_2O_3) / n(K_2O) \quad (\text{Eq. 5})$$

$$S_{sp} = 6 / r \cdot d_1 \quad (\text{Eq. 11})$$

$$S_{sp} = 6 / r \cdot S(N_i / d_i) \quad (\text{Eq. 12})$$

$$S = S_{sp} \cdot C_s \quad (\text{Eq. 13})$$

$$k_{dec} = k_{lg} \cdot S \cdot r \cdot K_v \quad (\text{Eq. 14})$$

$$\frac{d \ln K}{dT} = \frac{E_a}{(R \cdot T^2)} \quad (\text{Eq. 15})$$

$$-\frac{dC}{dt} = k_{dec} (C - C_{eq})^2 \quad (\text{Eq. 16})$$

$$\Delta t_{dec} \geq \frac{\Delta C_{Al}}{-dC/dt} \quad (\text{Eq. 17})$$

$$\Delta C_{Al} = \Delta C_{Al^1} - \Delta C_{Al^2} = \frac{M_{Al}}{Q_{el}} \quad (\text{Eq. 18})$$

$$\Delta t_{dec} = \sum n \Delta t_i = \sum \frac{l_i}{w_i} \quad (\text{Eq. 19})$$

$$dt_{cr} = L_{cr} / W_{el} \quad (\text{Eq. 20})$$

$$V_{cr} = \frac{dC_{Al} \cdot Q_{el}}{dC/dt} \quad (\text{Eq. 21})$$

Figure 1. Schematic diagram of AA CCS

Figure 2. The dependence of induction time of the decomposition of aluminate solution on the concentration of aluminum; alkali concentration – 20 mass%. 1 – temperature 303K, 2 – temperature 333K, 3 – temperature 353K

Figure 3. The dependence of the induction time of the decomposition of the aluminate solution on the concentration of aluminum; alkali concentration – 16 mass%. 1 – temperature 303K, 2 – temperature 333K, 3 – temperature 353K

Figure 4. The dependence of induction time of decomposition of the aluminate solution on the concentration of aluminum; alkali concentration – 12 mass%. 1 – temperature 303K, 2 – temperature 333K, 3 – temperature 353K

Figure 5. The boundaries of state regions of aluminate solution depending on temperature; alkali concentration – 20mass%. I is a stable region, II is the first metastable region, III is the second metastable region, IV is a labile region

Figure 6. The boundaries of state regions of aluminate solutions depending on temperature. 2, 4 – a solution of 20 mass% KOH; 3, 5 – solution of 12 mass% KOH; I is a stable region, II is the first metastable region, III is the second metastable region, IV is a labile region

Figure 7. Differential size distribution curve for the seed crystals

Figure 8. Dependence of the decomposition rate in aluminate solution on alkali concentration. Temperature – 333 K; degree of supersaturation – 1.5; concentration A1 (OH)₃ – 2 mass%

Figure 9. Dependence of decomposition rate of aluminate solution on temperature. Alkali concentration – 20 mass%; degree of supersaturation – 1.5; concentration A1 (OH)₃ – 2 mass%

Figure 10. Dependence of the rate of decomposition of aluminate solution on the concentration of aluminum. Temperature— 333 K; KOH concentration – 20 mass%, $Al(OH)_3$ concentration – 2 mass%

Figure 11. Dependence of the rate of decomposition of aluminate solution on the concentration of aluminum hydroxide. Temperature – 333K; KOH concentration – 20 mass%; 1 – concentration $Al(OH)_3$ – 6 wt.%; 2 – concentration $Al(OH)_3$ – 4 wt.%, 3 – concentration $Al(OH)_3$ – 2 mass%

Figure 12. Dependence of decomposition rate constant on the seed surface. Temperature – 333 K; KOH concentration – 20 mass%

Figure 13. Scheme of the crystallizer: 1 – housing; 2 – drum; 3 – fitting for introducing the solution; 4 – fitting for withdrawing a suspension of crystals; 5 – a partition; 6 – paddle mixer; I – solution; II – suspension; III – cooling water