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AUTOMATED CONTROL SYSTEM OF EXTRACTION COLUMN

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Extraction column has been analyzed as a control object; its mathematical description has been developed subject to the peculiarities of processing. On the basis of mathematical description the simulation model of column device was developed. Automated control system was synthesized by re-extract density in pulse column. Estimation of control quality supported by the system was carried out.

Extraction technologies were widely adopted in radiochemical industry; their use allows supporting substance separation. Pulse column extractors connected step-by-step are used in reject fuel processing for hardware design of these technologies.

To decrease production costs, increase safety and change elemental base of controlling means in the devices for processing spent fuel (SF) the task of development of automated control system (ACS) of re-extraction process in extraction column, being a part of the device, was set.

In papers [1–3] extraction process modeling in column devices is examined, however, the results obtained their do not allow developing the efficient automated control system. The models developed before contain simplified differential equations the solutions of which do not support the required accuracy of process modeling.

Scientific novelty of this paper is in development of extraction column model as a control object that allows designing automated control systems operating in real time. Installation of automated control system at extraction column is a new engineering solution as well. Development of qualitative automated control system by re-extraction process allows increasing its safety, improving production engineering-and-economical performance.

The studied object (Fig. 1) represents the unique device for irradiated fuel processing by extraction technique [4] it includes 5 extraction plate-type pulse columns (EC).

The head extraction column EC1 is intended for uranium and plutonium extraction and wash-out of fission products from organic phase by descending current of nitro-acid water solution. Further extract washing occurs in column EC2 for removing highly active fission products and uranium and plutonium re-extraction occurs in EC3 and EC4. Column EC5 is intended for extractant washing.

Water flow – WF (continuous phase) and organic phase flow – OP (dispersed phase) enter the column EC4. WP flow is supplied by a pump and its consumption is controlled by local stabilization circuit. Water phase is extracted from lower sedimentation zone of EC4 by a built up pulse pump in the form of uranium re-extract. Pressure in receiver is stabilized by a local circuit by a valve.

EC4 column operation in manual mode implies increasing agent expenses. At excess inflow of water phase the expensive organic phase may be removed to re-extract with water phase. Otherwise, at deficient inflow of water phase metal goes into extractant. Stabilization of organic phase density and therefore, uranium concentration at specified level allows decreasing economic losses. This very fact stipulates the choice of EC4 column as a control object for the developed automated control system.

Examining the cascade as a whole it is seen that consumption of OP flow influences the technological processes in all columns therefore it can not be considered as a control action for EC4. It can not be used as a control one therefore, change of water phase consumption is chosen for control.

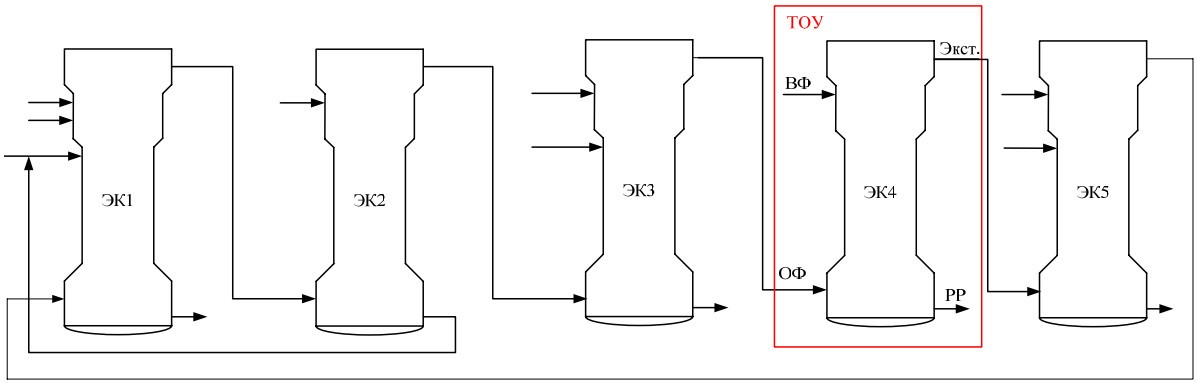

Fig. 1. *Simplified scheme of extraction cascade. ВФ – WP – water phase, ОФ – OP – organic phase, РР – RE -re-extract, Экстр. – Extr. – extractant*

Let us give a description of PUREX (plutonium-uranium extraction)-process occurring at the given device. In PUREX-process extraction methods are used for purification and separation of uranium and plutonium. Dissolved irradiated fuel $UO_2(NO_3)_2$ serves as a basic material. 30 % (by volume) solution of tri-n-butylphospate (TBP) $(C_4H_9O)_3PO$ in solvent of the type «kerosene» is used as extractant; salting-out agent is nitric acid. Separation is based on extractability of nitrates of uranyl and tetravalent plutonium and inability of fission products and trivalent plutonium to transfer to organic phase [5]. In the given case re-extraction reaction occurs:

$$UO_2(NO_3)_2 \cdot 2(C_4H_9O)_3PO \rightarrow UO_2(NO_3)_2 + 2(C_4H_9O)_3PO.$$

The following methods of modeling [6] extraction/re-extraction processes [7] are the most widely spread in column reactors: theory of similarity, hydraulic modeling and mathematical modeling.

The method of mathematic modeling was used. This method is used when designing a set of applied chemistry processes but practical application of the method for mass-transfer apparatus is difficult owing to the necessity of preliminary defining total coefficient of mass transfer and coefficients of longitudinal and radial dispersion in phases [5, 7]. As there is no reliable technique for computing these parameters at present and they have to be determined experimentally, application of mathematical modeling techniques for the processes of mass transfer is limited by special cases. In this case one-parameter diffusion model is used subject to stirring in both phases [5].

The equations of convective diffusion nonsteady in time at substance transfer from one phase to another one have a form [4, 5, 8]:

$$\begin{cases} \dfrac{\partial x}{\partial t} = -U_1 \dfrac{\partial x}{\partial h} + D_1 \dfrac{\partial^2 x}{\partial h^2} + W, \\ \dfrac{\partial y}{\partial t} = U_2 \dfrac{\partial y}{\partial h} + D_2 \dfrac{\partial^2 y}{\partial h^2} + W, \end{cases} \quad (1)$$

where U_1, U_2 are the rates of phase flow; D_1, D_2 are the liquid diffusion coefficients; h is the column height;

$$W = \beta_1 a(x^* - x) = \beta_2 a(y - y^*),$$

where β_1 and β_2 are the coefficients of mass transfer from one phase to another; a is the contact surface of two phases by a unit of volume; x^*, y^* are the equilibrium values of uranium concentrations in organic and water phases;

Diffusion coefficient D of liquids is so small that at low rates of liquids the convective substance transport considerably dominates over molecular diffusion. To simplify expression (1) the term of equation containing D is usually neglected:

$$\begin{cases} \dfrac{\partial x}{\partial t} = -U_1 \dfrac{\partial x}{\partial h} + \beta_1 a(x^* - x), \\ \dfrac{\partial y}{\partial t} = U_2 \dfrac{\partial y}{\partial h} + \beta_2 a(y - y^*). \end{cases} \quad (2)$$

The simplified equation of convective diffusion (2) – the equation in partial derivatives at a first approximation describes the processes in counter-current columns [5, 7–9]. However this equation supposes that rates U_1, U_2 are constant. In the developed model rates change depending on time, coordinate and uranium concentration. In this connection the equations of the system (2) become nonlinear differential ones the analytical solution of which is difficult.

System (2) can not describe with sufficient accuracy the re-extraction process in the column EC4. Rates of phase flow are not only changeable in time but also differ in column height. To obtain reliable results the described system should be complemented with the equations describing this dependence. To exclude height derivative from equations a number of stages is used. For each stage its own material balance equation is solved. Stages are connected in series. This method is called the analytical calculation by extraction stages [5, 10].

The following assumptions are accepted developing the model.

1. The model of ideal displacement is used for continuous phase [7]. Re-extract consumption equals to consumption of input liquid phase. The fact that the ratio of column displacement height to its diameter is rather high (more than 20) allows using this model.

2. Nitric acid does not transfer into organic phase. Influence of nitric acid concentration on uranium re-extraction process is not taken into consideration. This assumption works as acid concentration in water phase is very low (does not exceed 0,01 %).
3. At each stage of the column the equilibrium between dissolved substance content in both phases is established [4, 5].
4. Extraction rate is very high, re-extraction inertia is insignificant and therefore, it is not taken into account (equilibrium is instantly established) [5].
5. Intensity of liquid pulsation is the same at all stages (the model of ideal displacement is used).
6. As temperature changes in the column have high inertia liquid temperature in the column may be considered as constant. Temperatures of all input and output flows are the same, heat exchange between phases and environment is not taken into account.

In the model only the process of uranium re-extraction is considered. Processes connected with fission fragments are not taken into account as their concentration is negligibly small. Carry-over of a part of TBP with liquid phase is not examined as well.

Input parameters of the column are flows and concentrations of continuous and dispersed phases as well as physical parameters of a stage (diameter, height, frequency and pulsation amplitude). The separation factors by height are specified for the column (taken from reference book); on the basis of these factors the uranium concentration distribution in dispersed phase is calculated for each stage. Initial rate of dispersed phase and input uranium concentration in continuous phase are found from column static mode of operation.

The simplified algorithm of stage operation is given in Fig. 2.

At the beginning volumes occupied by continuous and dispersed phases as well as output flows of these phases are calculated. The obtained data allows calculating using the analytical method of calculation by extraction stage [5, 10] the change of uranium and acid concentration in both phases solving numerically the differential equation of material balance. Phase densities are searched for the obtained state of the system; dispersed phase rate which influences the phase consumptions and is required for the further iterations of calculations is recalculated.

Buoy density meter is a bit lower than the last stage therefore, it is necessary to take into account the delay time $t_{зап}$ of dispersed phase in lower sediment zone (LSZ) for obtaining reliable results. Owing to LSZ column delays about 1000 s; it changes to one or another side depending on phase motion rate:

$$t_{зап} = \frac{V_{НОЗ}}{Q_{спл}},$$

where $V_{НОЗ}$ is the LSZ volume; $Q_{спл}$ is the consumption of continuous phase.

To reveal the required quantity of stages in simulation model the experiments were carried out at the model increasing the amount of stages and mean square error between the current transient and previous one was calculated.

It was stated that it is necessary and sufficient to have ten stages for obtaining reliable results. Further increase of stage amount does not result in decreasing mean square error.

The designed construction of dependence diagram of uranium concentration distribution was carried out by co-

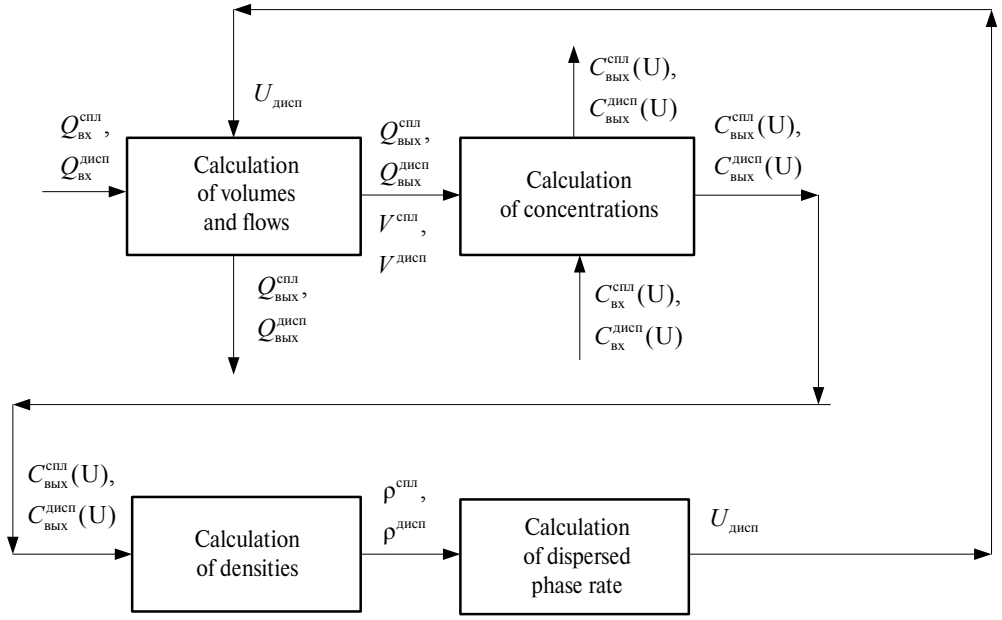

Fig. 2. *Simplified type of column stage model. $Q_{вх}^{спл}$, $Q_{вх}^{дисп}$, $Q_{вых}^{спл}$, $Q_{вых}^{дисп}$ are the input and output flows of continuous and dispersed phases; $V^{спл}$, $V^{дисп}$ and $\rho^{спл}$, $\rho^{дисп}$ are the volumes and densities of continuous and dispersed phases; $C_{вх}^{спл}(U)$, $C_{вх}^{дисп}(U)$, $C_{вых}^{спл}(U)$, $C_{вых}^{дисп}(U)$ are the input and output uranium concentrations in continuous and dispersed phases; $U_{дисп}$ are the rate of dispersed phase*

lumn height after changing certain parameters of processing. By the moment adequacy of the obtained results of modeling is tested experimentally. These experiments will be continued for further improvement of model operation.

At the moment the developed model is updated; the following sensors are realized: buoy level meter, neutron indicator of level deflection (level in a pulse chamber) and metal concentration meter. The model takes into account influence of temperature and nitric acid on chemical reaction. It allows complicating control system structure, using complicated control algorithms, increasing system quality.

The developed simulation model of re-extraction process in the column EC4 is nonlinear as the product of function itself and its derivative enter into differential equation describing extraction stage therefore its linearization is required. To construct linear model it is necessary to ascertain in what range of variable changing the obtained simulation model is linear. For this purpose the corresponding experiments were carried out at the model. Step excitations of different amplitude were supplied through a pilot channel (water phase consumption).

The analysis of the results shows that at nonlinearity in the range of 15 % in comparison with static characteristic the model is linear at change of consumption of continuous water phase (control coordinate) in the range of ±15 % from the initial point. The measured (controlled) coordinate changes in the range of (–0,8; +1) %.

Therefore, the simulation model EC4 may be replaced by the linear one in the neighborhood of working point in the range of ±15 % from the regulation value of WP consumption.

To develop control system the transfer function by water phase consumption is of interest (the rest functions may be needed at regulator disturbance-variable compensation calculation by the given channels).

Let us make a block diagram of automated control system.

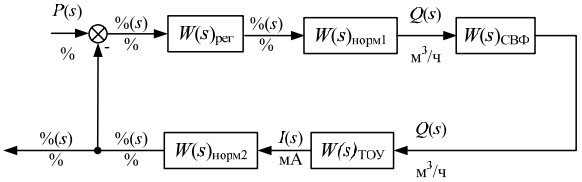

Fig. 3. *Block diagram of ACS of $W(s)_{рег}$, $W(s)_{норм}$, $W(s)_{норм2}$, $W(s)_{СВФ}$, $W(s)_{ТОУ}$ the transfer functions of regulator, normalizing converters 1 and 2, local circuit of WP consumption stabilization, technological control object (TCO) respectively*

To simplify further calculations let us combine all the elements except regulator in one element – generalized object.

By controlling channel a linearized model is aperiodic link of the first order with delay. In terms of abovestated let us set our choice on regulators of PI type (proportional-plus-integral action) and PID (proportional-integral-differential) as the most universal ones.

To calculate transients of closed ACS the software product «SarSintez» developed at TPU department of electronics and physical device automatics was used. Besides calculations of transients of closed ACS by perturbation action this software product allows determining control time and dynamic coefficient of overcontrol.

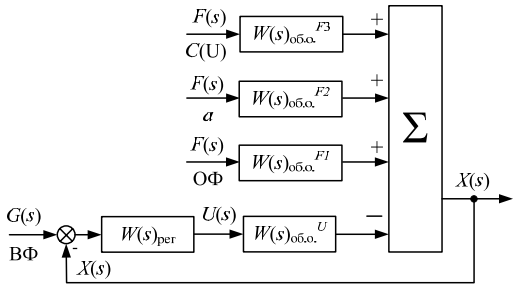

Fig. 4. *Simplified block diagram of ACS of $W(s)_{рег}$, $W(s)^{F1}_{об.о}$, $W(s)^{F2}_{об.о}$, $W(s)^{F3}_{об.о}$, $W(s)^{U}_{об.о}$ regulator transferred functions, generalized object by disturbance and control respectively*

ACS EC4 was experimentally investigated at computer model of the system developed in the package Matlab/Simulink V. 6.5 [11]. Perturbations were supplied to system input by all channels and control quality was estimated. Diagrams obtained as a result of model investigation are given in Fig. 5–8. All perturbations were supplied at time moment t_0=600 s.

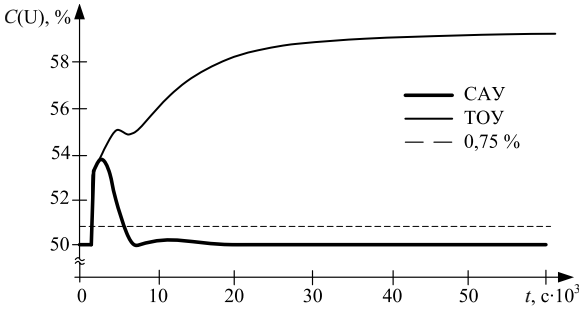

Fig. 5. *Reaction of ACS and TCO on a change of OP consumption by 15 %*

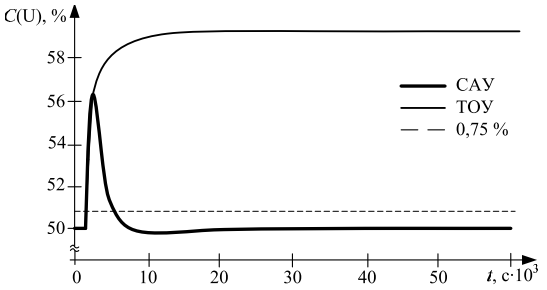

Fig. 6. *Reaction of ACS and TCO on a change of uranium concentration in OP by 15 %*

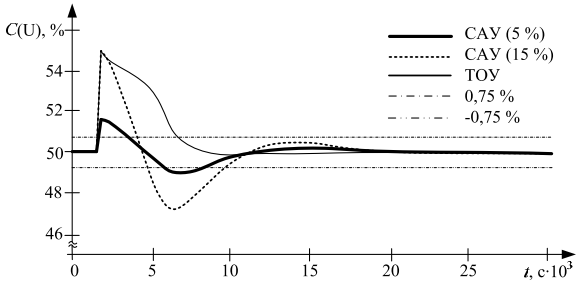

Fig. 7. *Reaction of ACS and TCO on a change of pulsation amplitude in the column by 5 and 15 %*

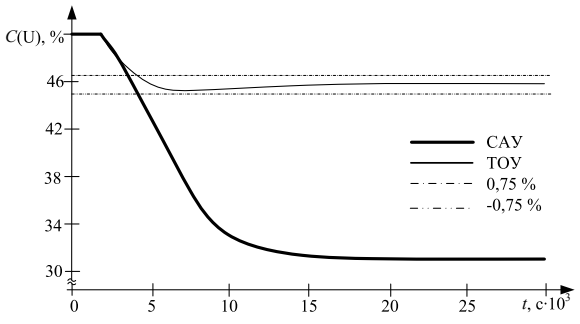

Fig. 8. *Reaction of ACS and TCO at setting change by 4 %*

Synthesized ACS shows the results meeting made demands. Considerable control time at pulsation amplitude change is connected with the difference of transfer function of TCO by control and by the given perturbation. To decrease control time it is necessary to enter more strict requirements to pulsation amplitude stability in this case.

As a result of the performed work the following problems were solved:

- Re-extraction process in column EC4 was analyzed.
- Simulation model of the column EC4 was developed.
- ACS of EC4 was developed.
- Simulation model and ACS were implemented as a computer model in program package Matlab/Simulink V. 6.5.
- ACS was experimentally investigated.

Automated control system by re-extraction process in re-extraction column was introduced at Radiochemical plant of Siberian chemical enterprise that allowed improving significantly techno-economic indices, increasing safety and reliability of production.

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