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Automatic Control System of the Evaporator in the Technology of Spent Nuclear Fuel Processing

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The operation of the radiochemical plant is impossible without high-quality automatic control systems. In the technologies of spent nuclear fuel reprocessing, the method of continuous evaporation is often used for a solution conditioning. The effective continuous technological process will depend on the operation of the evaporation equipment. In this paper, the method of mathematic simulation is applied for the development and research of evaporator control system. Two systems were considered. Parameters of regulators were calculated and direct quality indicators were presented. As a result, an automatic control system with the low sensitivity of the system to the density variation was chosen.

1. Introduction

Currently, for the implementation of a closed nuclear fuel cycle, it is necessary to create a laboratory unit for testing extraction-crystallization technology for the processing of spent nuclear fuel.
One of the components of this unit is a crystallization unit, whose efficiency strongly depends on the efficiency of the evaporator. This unit is designed for evaporation of the uranium solutions. Performance indicator of the evaporating equipment is the ratio of power consumption for obtaining a solution with a set concentration and the expenses to minimize entrainment of impurities in the steam. The purpose of automatic control of the evaporation process is to obtain a solution of a set concentration, and also to maintain mass and heat balances. The essential difference of the discussed evaporator from the similar industrial units of chemical technology is its small volume, which meets nuclear safety requirements. The key features that make the development of the automatic control system (ACS) for this unit unique are the following: hydrostatic method of measuring density and level, and discrete control of free discharge.
Similar method is measuring density with two hydrostatic pressure sensors, described by Jivopistsev et al. (1999). Gofman (2012) improved this method, achieving lower measurement error and higher durability, which is necessary for extraction-crystallization technology. The control method for hydrostatic measuring of density and level, which introduces discrete control of free discharge, was presented by Gofman et al. (2012). Similar methods such as a quasi-hydrostatic method for measuring density (Remiorz and Ostrowski, 2015) and a method for observing density at high temperatures using dynamic pressure (Zhou et al., 2017) are being developed, but they are used for liquids flowing in a pipeline.

2. Analysis of the evaporation process as a control object

The operation principle of the laboratory evaporator is as follows. The inlet uranium solution enters the circulation pipe to a certain level determined by the unit structure. After that, the heating chamber is heated until the solution in the heat exchange tubes of the chamber boils. The resulting vapor-liquid mixture is separated in the separator. When the desired concentration of the solution is reached, the evaporated solution of uranium is discharged from the evaporator.
The boiling point of the solution depends on the temperature, density and steam pressure over it. According to the technological regulations, the solution temperature should be stabilized at the set value. The evaporation rate depends on the current used to heat the heating element of the heating chamber. The concentration of the

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evaporated solution is calculated by its density and depends on the flow rate, density of the feed solution and evaporation rate.

When draining the evaporated solution from the unit, mass balance is maintained, by keeping the equality between the amount of the solute draining from the unit, and the amount of the substance coming from the feed solution. The level of the solution in the evaporator is the major parameter of the evaporation process as the thermal and hydrodynamic operation of the unit depends on it.

The main controlled variables are the temperature of the solution, its level and its concentration / density in the unit. The manipulated variable is flow rate of the feed solution and the discrete signal of the outlet valve control.

3. Development of a mathematical model of evaporator

A mathematical model of uranium re-extract evaporation should reflect the time history, and mutual influence of the following variables:

i) level of the solution in the evaporator, with respect to the flow of the feed uranium solution;

ii) concentration / density of the evaporated solution, with respect to the flow and concentration / density of the feed solution;

iii) temperature of the solution in the unit with respect to the temperatures of the feed solution and the heating chamber.

iv) ratio of the evaporated solution with respect to the flow and concentration / density of the feed solution.

The main inlet variables of the model are the following:

i) flow rate of the feed solution;

ii) concentration of feed solution;

iii) temperature of feed solution;

iv) discrete variable, which is equal to 1, in case the heater is on, and 0 – if it is off;

v) discrete variable, which is equal to 1, in case the valve is opened, and 0 – if it is closed.

The main outlet variables of the model are the following: values of the solution level in the unit, concentration of the evaporated solution, the solution temperature in the unit, the temperature of the heating jacket and steam flow produced during evaporation of the solvent.

There is a variety of evaporators and modelling methods for evaporators. For Agitated Thin-Film Evaporator the finite volume method was used (Rossi et al., 2015), but this evaporator mixes the solution with rotating blades and the mechanical wiping device that produces and agitates the liquid film. Another model (Kozin, et al., 2016) of evaporator, which is similar to the one discussed in this article, was taken as a reference model. The main difference between them is the heating method of the feed solution.

The distinctive features of the mathematical model of the evaporator are the following: electrical heating method, the process temperature consideration, the use of a peristaltic pump for the flow rate control of the feed solution, the product discharge by the on/off valve, discrete control of the heater. The system of equations describing the developed evaporator is as follows:

$$
\begin{cases}
\dfrac{dh}{dt} = \dfrac{1}{A}\left(Q_V - u_k \gamma A_K \sqrt{2gh} + \dfrac{W_V}{\rho_W}\right) \\
\dfrac{d\rho}{dt} = \dfrac{1}{Ah}\left(W_V\left(\dfrac{\rho}{\rho_W} - 1\right) - Q_V \rho_V\left(\dfrac{\rho}{\rho_V} - 1\right)\right) \\
\dfrac{dT_A}{dt} = \dfrac{I^2 R_a}{F c_m} u_t - \dfrac{K S_p}{F c_m} T_A \\
\left[\begin{array}{l} W_V = \dfrac{Q_V \rho_V c_V T_V - u_k \gamma A_K \sqrt{2gh} \cdot cT}{i_V}, (for\ T \geq T_b + \alpha) \\ W_V = 0, (for\ T < T_b + \alpha) \end{array}\right. \\
\left[\begin{array}{l} \dfrac{dT}{dt} = \dfrac{\left[Q_V \rho_V (i_V - i) + W_V (i_V - i) - \lambda (T - T_A)\right]}{\rho_V c_V A h}, (for\ T \leq T_b + \alpha) \\ \dfrac{dT}{dt} = 0, (for\ T > T_b + \alpha) \end{array}\right.
\end{cases}
\tag{1}
$$

where A – the cross-sectional area of the evaporator, m^2; Q_V – the flow rate of feed solution, m^3/h; u_k – the discrete value of the outlet valve mode: opened / closed; γ – the valve flow coefficient; A_k – the sectional area of the valve, m^2; W_V – the mass flow of the steam, kg/h; ρ_V – the density of feed solution, kg/m^3; T_A – the temperature of the heating jacket, K; I – the current, used for heating the copper heater, A; R_a – the resistance, Ohm; u_t – the discrete value of the heater operation mode – on / off; F – the weight of the heater, kg; S_p – the cooling surface of the conductor, m^2; K – the total surface heat exchange coefficient; c_m – the specific heat capacity of the conductor material (copper), J/(kg·K); ρ_w – the density of water, kg/m^3; i – the enthalpy of steam, J.

4. Development of the evaporator control system

The most important parameter of the evaporation process that determines the quality of the finished product is concentration of the solution at the evaporator outlet (Nisenfeld, 1985). The concentration and the liquid level in the evaporator are interrelated parameters. Any exposure, which changes the concentration of the solution in the unit, also causes a change in a liquid level therein. It is possible to maintain a constant concentration of the solution at the outlet of the unit if a change in the feed flow was selected as a control action.
As a result, we have developed two kinds of ACS of the evaporator.
The block diagram of ACS №1 in the evaporation mode is shown in Figure 1, where GL, G_d, GT – setpoint values of the solution level L, its density d and the temperature T_A; Q_V, Q_{out} – inlet and outlet flow rates, PI – the proportional-integral controller, ε – error signals, u_k – a discrete value of the outlet valve mode (open / closed), u_t – a discrete value of the heating chamber mode.

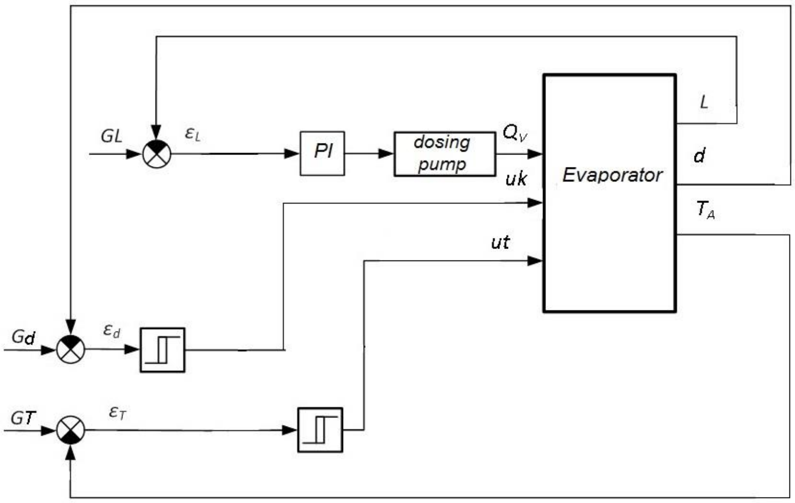

Figure 1: Block diagram of ACS №1

ACS №1 consists of the following three control loops:
i) density / concentration stabilization d using the relay controller of the outlet;
ii) level stabilization in the unit L using PI controller of feed flow Q_V and the overridable outlet valve mode;
iii) temperature stabilization of the solution in the unit T_A applying the relay algorithm of the heater which is overridable according to the aperiodic transient process of the density / concentration d.
Level and density of solution in evaporator are measured with two pressure differences (ΔP_1, ΔP_2) in three different points with use of differential pressure sensors (Gofman et.al. 2012). These points are at different heights of evaporator. Pressure measurement of controlled environment is done with three capillary pipes filled with separation liquid.
The solution density d in separation chamber is calculated as follows:
calculated as follows:

$$d = \rho_{sep} + \frac{\Delta P_2}{g} \cdot \Delta H \qquad (2)$$

where ρ_{sep} – density of separation liquid; ΔH – length between lowest points where pressure is measured, m; g – gravitational acceleration, m/s^2.
The solution level in evaporator is calculated as follows:

$$L = L_0 - \frac{\Delta P_2}{d \cdot g} \qquad (3)$$

where L_0 – constant, m.
The error signal between the setpoint and current values of density / concentration ε_d arrives at the relay with hysteresis. In case d exceeds an upper bound the relay controller produces a signal for opening the outlet valve.

To compensate the perturbation from the valve opening, the signal is generated which arrives to the level stabilization loop. Also the timer block receives the signal. If during the set time interval the value of d does not decrease, the timer block generates a signal for the stabilization loop to decrease a setpoint value of T_A. When d decreases to the setpoint value, the timer block turns off. At the same time, the relay controller switches over and the outlet valve closes and $\Delta T = 0$.
When evaporating weak solutions with volatiles, density - composition relationship is ambiguous. In particular, if concentration of nitric acid changes up to 10 mol/L, density change of the solution is observed. It makes impossible to use ACS №1 and requires the replacement of density stabilization loop with the loop of evaporation ratio stabilization.
As a result, ACS №2 consists of the following three basic loops (Figure 2):
i) the loop of evaporation ratio stabilization using PI controller of the outlet valve;
ii) the loop of the solution level stabilization in the unit *L* using PI controller of the feed flow Q_V;
iii) the control loop of the heater power in a heating chamber.
The block diagram of ACS №1 in the evaporation mode is shown in Figure 2, where *GL,* G_d*, GT* – setpoint values of the solution level *L*, its density d and the temperature T_A; Q_V, Q_{out} – inlet and outlet flow rates, *PI* – the proportional-integral controller, **ε** – error signals, D_{out} – the duration of the *PWM* signals of the outlet valve opening, u_k – a discrete value of the outlet valve mode (open / closed), u_t – a discrete value of the heating chamber mode.

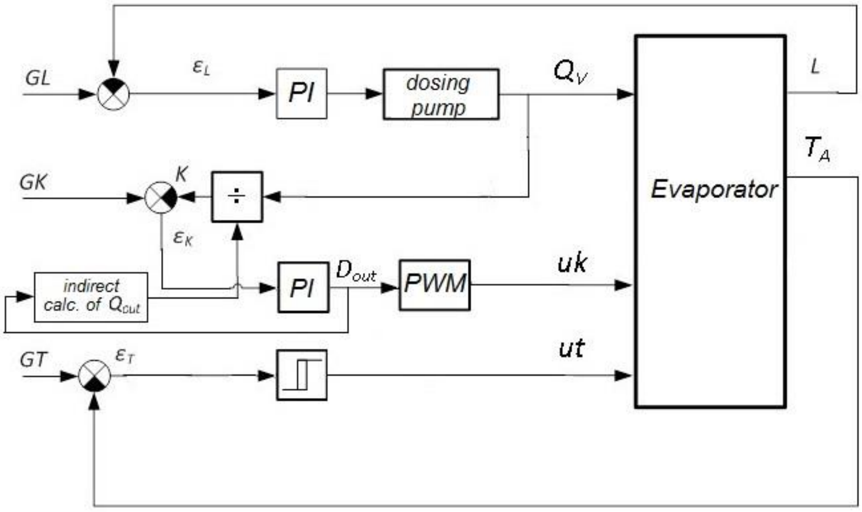

Figure 2: Block diagram of ACS №2

At the beginning of evaporation, the outlet valve of the evaporated solution is closed. When reaching the desired ratio PI controller produces a signal for opening the outlet valve. After that, the evaporation ratio is estimated as feed flow divided by indirectly calculated flow rate (Q_{out}) of the evaporated solution. Q_{out} is calculated as follows:

$$Q_{out} = \frac{D_{out}}{T_{PWM}} \cdot Q_{out}^{max} \tag{4}$$

where Q_{out}^{max} – the maximum setpoint value of the evaporated flow when the outlet valve is open, D_{out} – the duration of the PWM signals of the outlet valve opening, T_{PWM} – a set PWM period for the evaporation ratio controller.
The error signal between the set and the current evaporation ratio enters the loop of the heater power control. If the set ratio of evaporation cannot be achieved because of the temperature constraints, the relay controller generates a closing signal for the outlet valve, evaporation ratio calculation is reset and the algorithm is repeated.
To improve the control quality and reduce the risk of an accidental unit discharge, it is advisable to consider the flow rate control of the evaporated solution using the dosing pump.

5. Parametric synthesis of ACS

The static and dynamic characteristics of the controlled plant (CP) were determined and the values of the controller parameters were calculated to ensure stable operation and satisfactory control quality of the automatic control system (ACS).
The ACS transfer function through $Q_V \to \rho$ and $Q_V \to h$ channels can be described as an aperiodic element of the first order with the transfer function as follows:

$$W(s) = \frac{K}{Ts+1}, \quad (5)$$

where K – the transfer coefficient of the object; T – the time constant of the object.
CP is described by the aperiodic link instead of the integrating one, as the evaporated solution is discharged through the outlet valve. The outlet valve with pulse control can be described by a linear inertia-free element.
The static and dynamic CP parameters are described by the following equations:

$$T = \frac{A}{\gamma A_K}\sqrt{\frac{2\bar{H}}{g}}, \quad (6)$$

$$K = \frac{\sqrt{2\bar{H}}}{\gamma A_K \sqrt{g}} \quad (7)$$

The calculated parameters of the control object are shown in Table 1.

Table 1: Parameters of the controlled plant

Channel	Parameters	Values
$Q_V \to \rho$	K	-1.42 (kg/m^3)/(mL/h)
	T	0.62 h
$Q_V \to h$	K	4.112 (kg/m^3)/(mL/h)
	T	0.83 h

Denisenko (2008) states that the lack of delay in the control channels suggests inadvisability of using a proportional-integral-derivative (PID) control law. Demchenko (2001) recommends using more complex control laws for the objects with a significant delay.
PI controller settings were calculated using the dynamic compensation method, the optimal magnitude method and the Simulink application «Control Design PID Tuner». The comparison of direct indicators of PI controllers quality for each of the CP channels, demonstrated that the regulators, adjusted using the «PID Tuner» provide the best control quality (Table 2).

Table 2: Direct quality indicators of the ACS with PI controller

Channel	Direct quality indicators					
	Dynamic compensation method		Optimal magnitude method		«PID Tuner»	
	T_{reg}, min	σ, min	T_{reg}, min	σ, min	T_{reg}, min	σ, min
$Q_V \to \rho$	12.46	1.53	13.46	1.53	11.23	0.74
$Q_V \to h$	8.3	3.12	9.1	3.8	1.05	0.28

In addition to the PI controllers, relay controllers with hysteresis were used in the development of both ACS №1 and ACS №2. Since the controller operates together with the PWM modulator, in the periods when the valve is fully open or closed they can be described as a proportional link.

6. Study of transient processes

To investigate the evaporator ACS a series of numerical experiments were conducted on the ACS models with the implementation of PI controllers and relay controllers in the MATLAB / Simulink software environment. The research of ACS transient processes allowed to determine the major direct indicators of the control quality, in particular settling time (Table 3).

Table 3: Direct quality indicators of ACS

Parameter	Settling time, ACS № 1	Settling time, ACS № 2
Density	45	-
Temperature	18	16
Level	30	28
Ratio	-	38

The evaporator control must take into account the relationship between the control channel of the level and control channel of the density. For example, if the maximum control rate of the system in the density / concentration channel is achieved, a local level control loop will not be able to keep it at a setpoint value. In this case there could be significant variations of level, which might damage the unit. On the other hand, if it is necessary to provide maximum control rate to achieve the desired level of the system, variations of density / concentration of the solution will be observed. In continuous operation of the evaporator, involved in a complex process, it can have a negative impact on the quality of the finished product. While designing the evaporator control system it is necessary to observe balance between system control rate and maximum possible variations of the basic process variables.

The main disturbance significantly affecting the performance of the evaporator control system is density variation of the feed solution ρ_V. 8 % decrease of this parameter leads to a level drop and substantial increase of the settling time.

7. Conclusion

Considering the characteristics of the synthesized control systems and the fact that the CP is still at the development stage, ACS №1 can be recommended for the experiments aiming at the determination of the optimal value of the solution level in the unit, which provides the best circulation of the solution.
Due to the low sensitivity of the system to the density variation, ACS №2 can be recommended for such processes as raffinate evaporation of various concentrations.

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