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A Computer Model of the Evaporator and Its Sensors

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For the implementation of a closed nuclear fuel cycle it is necessary to carry out a series of experimental studies to justify the choice of technology. 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. Therefore, the effective continuous technological process will depend on the operation of the evaporation equipment. Its essential difference from similar devices is a small size. In this paper, the method of mathematic simulation is applied for the investigation of one-effect evaporator with an external heating chamber. Adequacy was tested using the experimental data obtained at the laboratory evaporation unit. The results proved that the studied subject is a Multiple Input Multiple Output (MIMO) plant, nonlinear over separate control channels and not self-balancing.

1. Introduction

Evaporation is conditioning of liquid waste and concentration of the desired products. Evaporation and specifically evaporators are used in different technological processes. For example, modelling, identification and control of evaporation presses was described by Lissane et al. (1999). The method of evaporation is often applied for conditioning solutions in spent fuel reprocessing technologies. The effective continuous operation of the technological process will depend on the operation of the evaporation equipment. Its essential difference from similar devices is a small size due to a relatively small-scale production for safety assurance. Existing models of evaporators mostly used for processes without high safety requirements of spent nuclear fuel production such as digestate thickening in biogas plants (Vondra et al., 2016) and sugar concentration in ethanol production (Prado et al., 2015). Such devices are MIMO plants, nonlinear over separate control channels and they are not self-balancing. To study various automated control system (ACS) using a one-effect evaporator with an external heating chamber for evaporation of uranyl nitrates solution (see Figure 1), it is necessary to create a mathematical model describing the dynamic relationships between key process variables. At the same time, according to a general engineering rule, for the synthesis of ACS 10 % accuracy is quite acceptable, due to the approximate formulas for analytical calculations of the controller parameters (Sovetov and Yakovlev, 1998). Another system allowing 20 % accuracy was presented in Scarpa et al. (2015) article.

2. Mathematical model

The block diagram of evaporator is shown in Figure 1, where Q_r, Q_p, Q_f – the volume flow of reflux, the evaporated uranium re-extract and feed solution of uranium re-extract, m^3/h; T, T_r, T_f, T_s – the temperature of reflux, solution in the unit, feed solution of uranium re-extract and heating steam, °C; ρ, ρ_V, ρ_r, ρ_f – the density of the solution in the unit, secondary steam, reflux, feed solution of uranium re-extract, kg/m^3; W_k, W_s, W_V – the mass flow of the condensate, heating and secondary steam, kg/h; P_s, P_V – the pressure of the heating and secondary steam, kPa; i, i_s, i_f, i_r, i_v, i_p – the enthalpy of the solution in the unit, the heating steam, the feed solution, reflux, secondary steam and the evaporated uranium re-extract, J/kg; C, C_f – the concentration of the evaporated uranium re-extract and the feed solution of uranium re-extract, kg/m^3.

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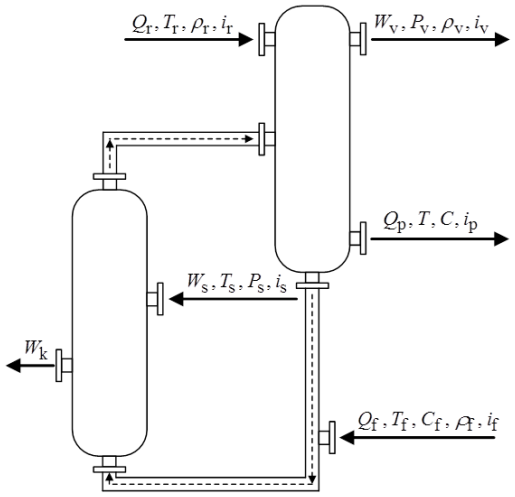


Figure 1: Evaporator scheme showing input and output variables

A mathematical model of uranium re-extract evaporation should represent the following:
1) Time history of the solution level in the unit according to the flow of feed solution of uranium re-extract, evaporated uranium re-extract, reflux and heating steam flow;
2) Time history of concentration/ density of evaporated solution, depending on the flow rate and the concentration/ density of the feed solution and the reflux, flow of the evaporated uranium re-extract and heating steam;
3) Time history of the solution temperature in the unit depending on the temperature of feed solution, reflux, heating steam and its pressure.
The model should take into account mutual influence of the controlled parameters, mentioned above.
Mathematical formulation for analytical models of chemical units is based on generation of equations for mass and heat balance of the system. Equations for an evaporator similar to the one presented in this article are used in the model by Kozin et al. (2016). Chursin et al. (2016) presented a model of separation process with formulation for concentration.
Mathematical formulation had to be simplified due to the lack of data on the thermodynamic properties of the evaporated product, physical and thermodynamic parameters of the heating and juice steam, as well as the necessary data for the description of the heat lost to the environment etc.
As a result, time history of the material, element and heat flows in the unit is described by the Eq(1), where A – cross sectional area of the evaporator, m^2; c_f – specific thermal capacity of the feed solution, kJ/(°C·kg); ρ_w – water density, kg/m^3 and the mass flow of secondary steam W_v is calculated by the Eq(2).

$$\begin{cases} \dfrac{dh}{dt} = \dfrac{1}{A}\left(Q_f + Q_r - Q_p - \dfrac{W_v}{\rho_w}\right) \\ \dfrac{d\rho}{dt} = \dfrac{1}{Ah}\left(W_v\left(\dfrac{\rho}{\rho_w} - 1\right) - Q_f\rho_f\left(\dfrac{\rho}{\rho_f} - 1\right)\right) \\ \dfrac{dT}{dt} = \dfrac{\left[W_s\left(i_s - i_c\right) + Q_f\rho_f\left(i_f - i\right) + Q_r\rho_r\left(i_r - i\right) + W_v\left(i_v - i\right) - L\left(T - T_{ar}\right)\right]}{\rho_f c_f Ah} \end{cases}, \tag{1}$$

$$W_v = \frac{Q_f\rho_f c_f T_f - Q_p\rho cT + Q_r\rho_r i_r + W_s i_s}{i_v}. \tag{2}$$

Enthalpy of heating steam, secondary steam, and dew is determined using the expression obtained by fitting the tabular data:

$$\begin{aligned} i_{s,v} &= 2.5\cdot 10^6 + 1813\cdot T_{sat} + 0.417\cdot T_{sat}^2 - 0.11\cdot T_{sat}^3 + 2090\cdot\left(T_{s,v} - T_{sat}\right) \\ T_{sat} &= \frac{2147}{\left(10.76 - \lg(P_s)\right)} - 273.2 \\ i_c &= \left(-0.0051\cdot T_s^2 - 1.5595\cdot T_s + 2467.1\right)\cdot 10^3 \end{aligned} \tag{3}$$

The developed approach and mathematical description of the evaporator as a controlled object was implemented as a computer model in the MATLAB/ Simulink package.
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 (see Figure 2).

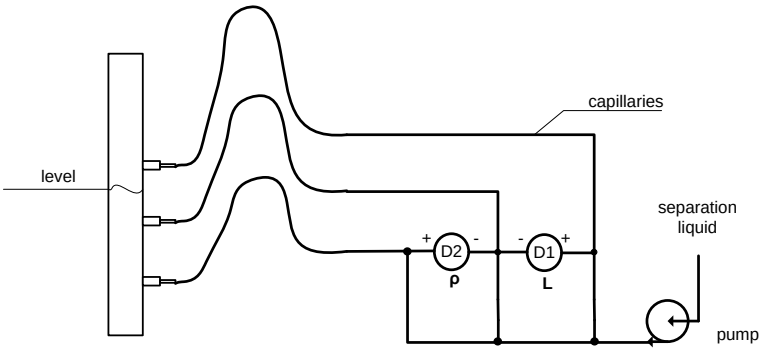


Figure 2: Block diagram of density and level measurement

The solution density ρ in separation chamber is calculated as follows:

$$\rho = \rho_{sep} + \frac{\Delta P_2}{g} \cdot \Delta H \tag{4}$$

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:

$$L = L_0 - \frac{\Delta P_2}{\rho \cdot g} \tag{5}$$

where L_0 – constant, m.
Linear pressure and density dependence was acquired experimentally. Experimentally obtained pressure and level dependences for different solution density is shown in Figure 3.

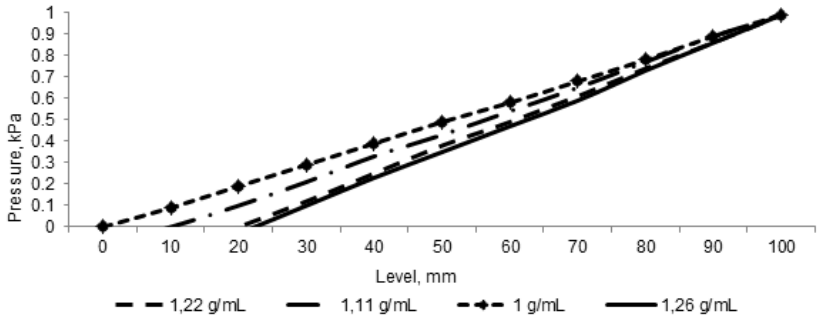


Figure 3: Pressure and level dependences for different solution density

For testing qualitative adequacy of the model, research results of the evaporators presented by other researchers were used (Taubman, 1970). One of the study subjects there was a two-stage vacuum evaporator "Edinstvo".

3. Simulation results

Figure 4 shows the transition processes of the solution level in the second device of "Edinstvo" evaporator and in the developed model of uranium re-extract evaporator. The flow of the feed solution ΔS_p = 1,700 kg/h to the unit was changed up to 62 %.

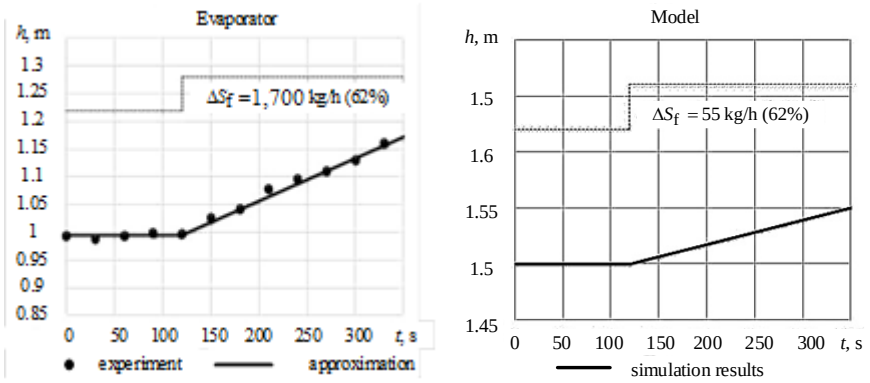
As it is seen from the graphs, the behaviour of the level in both cases is identical, and the channel of the controlled object can be regarded as an astatic link.

Figure 5 shows the transient responses of the concentration in the first device of "Edinstvo" evaporator and the appropriate transitional process in the developed computer model of the evaporator. The fluid flow from the unit ΔS_p = -250 kg/h was changed up to 30 %.

The above graphs show that transient responses of concentration obtained at the evaporator and the simulation results are qualitatively equal. In addition, this channel of the controlled object can be regarded as a first order aperiodic link.

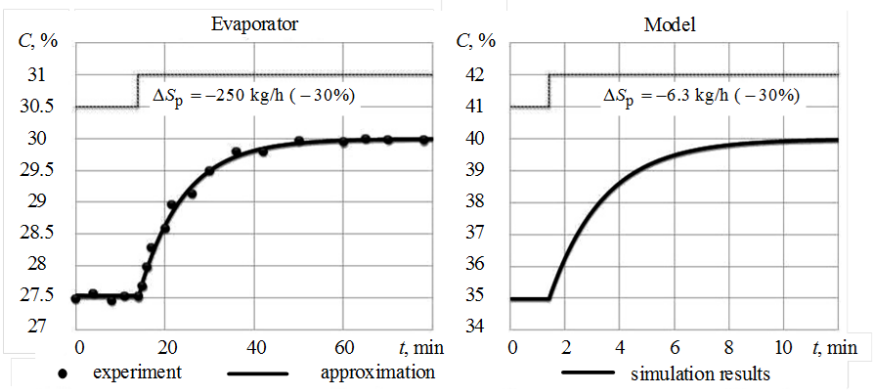
Figure 6 shows the transient responses of the temperature of the solution in the first device of "Edinstvo" evaporator and the appropriate transitional process in the developed computer model of the evaporator. The heating steam flow from the unit ΔS_p = 480 kg/h was changed up to 17 %.

The above graphs show that the transient responses of temperature, obtained at the evaporation unit and the simulation results are qualitatively equal.



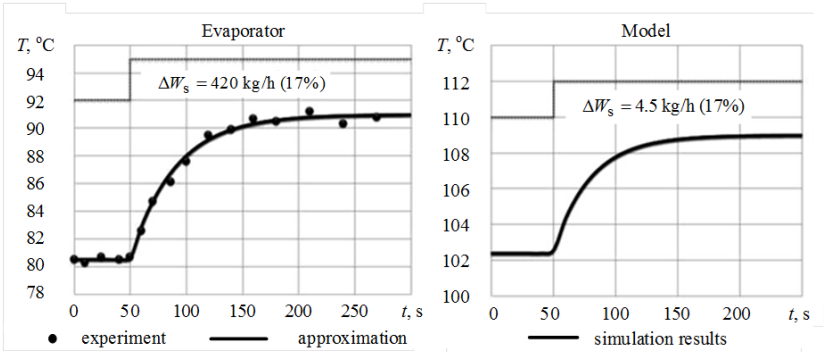
(a) Level (evaporator) (b) Level (model)

Figure 4: Transition process in the level



(a) Concentration (evaporator) (b) Concentration (model)

Figure 5: Transition process in concentration



(a) Temperature (evaporator) (b) Temperature (model)

Figure 6: Transition process in temperature

Similarly to the transient responses of concentration, it can be seen that the object of the present channel can be regarded as a first order aperiodic link. Comparison of simulation results with the data presented by Kam et al., (2002) shows their qualitative agreement.

The analysis of the given above transient responses shows that the time constant of the evaporators for concentration/ density is substantially higher than time constant for the level and temperature. This fact should be considered when developing ACS of an evaporation unit.

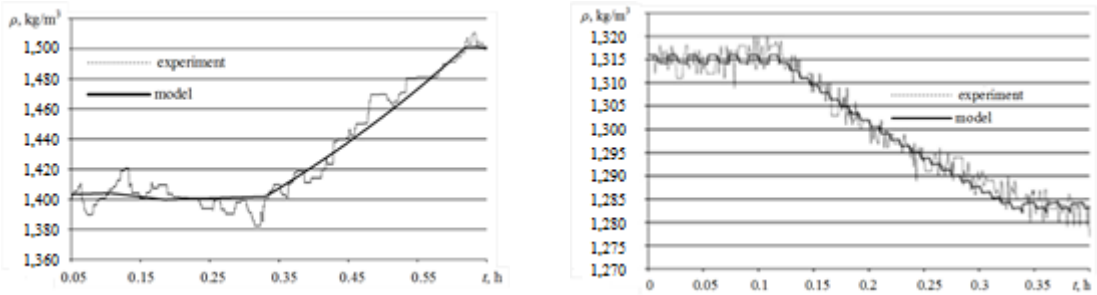
Qualitative adequacy of the developed model was tested using the experimental data obtained at a laboratory evaporator at V.G. Khlopin Radium Institute, St. Petersburg, Russian Federation.

This unit is equipped with an automated control system, based on two control algorithms. The first algorithm is designed for evaporation mode with a required density. The level of the solution in the still is maintained constant by controlling the flow of feed solution. In the transient mode (to achieve the desired density) the solution in the still was not drained. In the continuous mode, the solution was drained in proportion to the average flow of the feed solution. The second algorithm provides required density of the solution at the output of the evaporation unit in a continuous mode. The desired density of the solution in the still was maintained by the flow of feed solution, while the level was maintained by draining the solution in the still.

The following experiment was carried out at the laboratory evaporator. In the starting mode, after initial filling with the feed solution and beginning of the evaporation process control was maintained by the first algorithm in the transient mode. After reaching a required value of density ρ = 1,400 kg/m^3, that is, tapering off to a steady-state regime, control was maintained by the second algorithm. If the measured density of the solution in the still was greater than ρ, the maximum flow rate of feed solution was set. If it was less than that, the minimum flow rate was set. That is, the control was maintained according to the relay rules. After tapering off to a steady-state regime, transition process was recorded while set point of density was changed from ρ = 1,400 kg/m^3 to ρ = 1,500 kg/m^3.

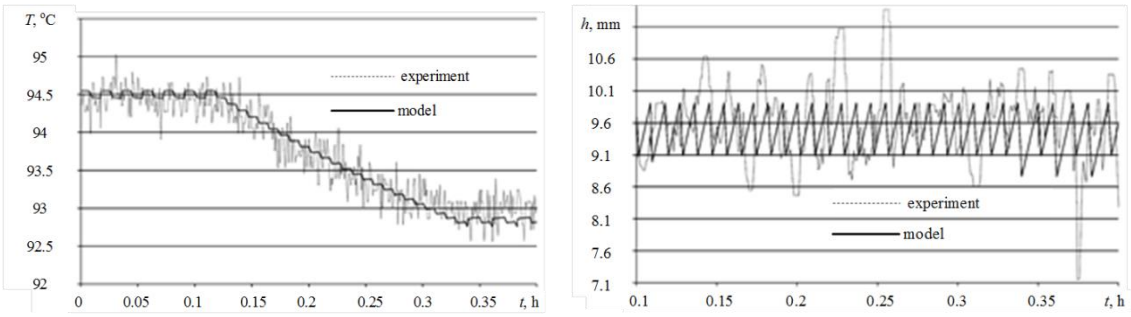
A similar experiment was carried out on the developed computer model of the evaporation unit. The experimental data and simulation results are shown in Figure 7(a).

Another experiment was carried out at the laboratory evaporator. After reaching a required density value of ρ = 1,315 kg/m^3, it was decreased to ρ = 1,285 kg/m^3. The results of the experiment are presented in Figure 7(b), Figure 8(a, b).



(a) density (b) density (second experiment)

Figure 7: Transition process in density for first (a) and second experiment (b)



(a) temperature (b) level

Figure 8: Transition process in temperature (a) and level (b)

4. Conclusion

Implementation of a closed nuclear fuel cycle requires substantiation of spent nuclear fuel technology through studies at the experimental and pilot equipment. At the same time, the creation of an effective radiochemical production with regard to its high radioactive, nuclear and environmental hazards is impossible without the use of automatic control systems. Mathematical model is required to develop an ASC. Mathematical model of an evaporator presented in this article has the relative standard errors of simulation in the level, density and temperature of the solution being less than 9 %, 5 % and 7 %. That allows its application for the development of ACS of an evaporation unit. Described method of the solution density and level measuring in the unit showed its efficiency and can be used in process control system.

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References

Chursin, Y.Y.A., Gozhimov, A.A.I., Liventsov, S.S.N., Shmidt, O.O.V., 2016, Mathematical model of separation of transplutonium and rare earth elements by ion-exchange chromatography method with complexation during elution, Chemical Engineering Transactions, 52, 199-204.

Gofman, F.E., Gofman, R.D., Zilberman, B.J., Rjabkov, D.V., Andreeva, E.V., 2012, Laboratory stand evaporator with an automated control system, Chemical Technology,13-9, 565-570.

Kam K.M., Saha, P., Tadé, M.O., Rangaiah, G.P., 2002. Models of an industrial evaporator system for education and research in process control, Developments in Chemical Engineering and Mineral Processing, 10 (1-2), 105–127.

Kozin K.A., Efremov E.V., Kabrysheva O.P., Grachev M.I., 2016. A computer model of the evaporator for the development of an automatic control system, IOP Conference Series: Materials Science and Engineering, 142-1, art. 012043, Yurga, Russian Federation

Lissane Elhaq, S., Giri, F., Unbehauen, H., 1999, Modelling, identification and control of sugar evaporation - theoretical design and experimental evaluation, Control Engineering Prectice, 7, 931-942.

Prado C., Souza O., Sellin N., Marangoni C., 2015, Comparison between single and multi-effect evaporators for sugar concentration in ethanol production, Chemical Engineering Transactions, 43, 541-546.

Scarpa F., Reverberi A., Tagliafico L.A., Fabiano B., 2015, An experimental approach for the dynamic investigation on solar assisted direct expansion heat pumps, Chemical Engineering Transactions, 43, 2485-2490.

Sovetov B.J., Yakovlev S.A., 1998. Modelling of Systems: Textbook for Universities, Visshaja shkola, Moscow, Russia, 344 ps.

Taubman E. I., 1970. Calculation and simulation of evaporators, Chemistry, Moscow, Russia, 216 ps.

Vondra M., Máša V., Bobák P., 2016, The potential for digestate thickening in biogas plants and evaluation of possible evaporation methods, Chemical Engineering Transactions, 52, 787-792.