Створено підхід до розробки прецизійних систем управління в промисловості на основі розробленого комплексу моделей, що враховують нелінійність моделі реактора, нелінійності гідродинамічного режиму і точність роботи регулюючих органів, нелінійність і точність роботи виконавчих механізмів, точність використаних датчиків. Розроблено багатовимірна прецизійна система управління хімічним реактором безперервної дії у виробництві синтетичного вітаміну B6

Ключові слова: прецизійна система автоматичного керування, реактор, вітамін B6, нелінійна математична модель

Создан подход к разработке прецизионных систем управления в промышленности на основе разработанного комплекса моделей, учитывающих нелинейность модели реактора, нелинейности гидродинамического режима и точности работы регулирующих органов, нелинейные характеристики и точности работы исполнительных механизмов, точность использованных датчиков. Разработана многомерная прецизионная система управления химическим реактором непрерывного действия в производстве синтетического витамина B6

Ключевые слова: прецизионная система автоматического управления, реактор, витамин B6, нелинейная математическая модель

UDC 681.51
DOI: 10.15587/1729-4061.2017.98941

DESIGN OF PRECISE CONTROL SYSTEMS OF INDUSTRIAL PLANTS

O. Stopakevych
PhD, Associate Professor*
E-mail: stopakevich@mail.ru
O. Ulitska
PhD*
E-mail: elenauli@ukr.net
*Department of automation of power processes
Odessa National Polytechnic University
Shevchenko ave., 1,
Odessa, Ukraine, 65044

1. Introduction

A prerequisite for the research is the potential for the design of high-precision automated control systems (ACS) of almost any complexity using advanced digital equipment.

Urgent problem is the actual application of such systems in industrial automation. Complex precise systems virtually exclude the adjustment stage from the start-up process. So, ACS should be modeled as accurately as possible before being put to use. This means that the synthesis and modeling of precise ACS shall consider:

– nonlinearity of the behavior of a real process;
– hydrodynamic operating conditions of controllers;
– properties of actuators;
– errors and dynamics of the chosen sensors.

This ensures the behavior proximity of ACS in modeling and in real operation conditions.

The urgency of the design of a precise ACS of a vitamin B_6 synthesis reactor is caused by the fact that vitamin B_6 is a valuable substance for the pharmaceutical, food and agricultural industries. Although vitamin B_6 can be produced in many ways, its long-term industrial production is based on chemical synthesis. The production process is completed by nitration of pyridone, fed as a suspension with acetic anhydride into a jacketed continuous stirred-tank reactor. The pharmaceutical industry requires a stable vitamin with minimum impurities. Stable composition, purity and prevention of potential process danger caused by the rate and exothermic nature of the reaction, are ensured by the precise ACS.

2. Literature review and problem statement

The literature review [1] shows that, despite a possibility of designing ACS of any complexity and quality, simple systems based on PID controllers prevail (up to 90 %) in the world industrial automation. At the same time, the precise control problem is paid attention to in the development of weapons [2], electric drives [3], robotics [4], precise mechanics [5]. In general, few works are available regarding the problem of precise control in industrial automation. The main reason is the established practice of simplified modeling of the control object and neglect of the control equipment properties.

One of the objects that require precise control is a pharmaceutical chemical reactor. For the design of high-precision ACS, modeling of the reactor is performed in the class of nonlinear lumped-parameter systems. Such modeling has been considered, for example, in the fundamental paper [6]. The number of the reactor equations depends both on the chemical conversions occurring in the reactor, and on the presence of thermodynamic reaction effects. This can be two equations for direct feedstock conversion into a product [7], or a chain of more equations for multistage feedstock conversion in view of thermodynamics [8]. The nonlinear model of a chemical reactor is sometimes considered as a family of linear models [9].

As a rule, adjustable parameters in the reactor are concentration of the final product, temperature and product level [6] that is neglected in simple cases. In addition to conventional PID controllers, neural networks and other artificial intelligence methods [10, 11], adaptive [9] and other types of controllers are also used. However, the designed ACS is not responsive to the properties of the control equipment operating in the system.

The literature on the control equipment considers the models of controllers, taking into account, for example, the geometry of valves [12], correlation between the controller friction and speed [13], etc. At the same time, modeling of such equipment and measuring system errors in combination with a dynamic model of an industrial plant has been hardly examined.

Among the pharmaceutical reactors, the focus of research is the vitamin B_6 synthesis reactor. Vitamin B_6 is a valuable substance for the pharmaceutical, food and agricultural industries. Although vitamin B6 can be produced in many ways, its long-term industrial production is based on chemical synthesis [14]. The production process is completed by nitration of pyridone, fed as a suspension with acetic anhydride into a jacketed continuous stirred-tank reactor. The pharmaceutical industry requires a stable vitamin with minimum impurities.

Thus, development of an approach to the synthesis and modeling of precise ACS, in particular, of the vitamin B_6 synthesis reactor, is a challenge.

3. Goals and objectives

The goal of the research is to develop an approach to the design of precise control systems of nonlinear objects. Based on the proposed approach, a modern precise control system of a reactor in the production of vitamin B_6 is developed.

In order to achieve the goal, the following objectives need to be accomplished:

– to develop a mathematical model of the dynamics of the control object;

– to develop a model of the variation of the hydraulic friction coefficient;

– to develop a model of the controller and automation equipment;

– to develop a precise ACS of the vitamin B_6 synthesis reactor.

4. Methods of research of objectives accomplishment in the design of precise control systems of nonlinear objects

A brief description of the research methods used to accomplish the objectives is given in Table 1.

The research was conducted with the help of the Matlab software system, including the Toolboxes Control System and System Identification. The resulting controller can be implemented in a real-time system using the Matlab Coder tool.

The design quality criterion is formed as a result of accurate modeling of the developed control system, which involved all the models obtained by accomplishing the objectives 1–5.

The transients resulting from the modeling should give small deviations in concentration (±6 mol/m^3), temperature (±1 °C) and level (±20 mm) of a product in the reactor under significant flow rate disturbances.

Small deviations in concentration ensure a high quality of vitamin B_6, small deviations in temperature and level of a product provide the process safety in the reactor.

5. Results of objectives accomplishment in the design of precise control systems of nonlinear objects

5. 1. Development of an analytical nonlinear mathematical model of the dynamics of a control object

In terms of modeling, the vitamin B_6 synthesis reactor is an ideal stirred-tank reactor, which receives flows of concentrated nitric acid and a suspension of pyridone with acetic anhydride. The reaction of pyridone with acid is exothermic, so the reactor includes a mixture cooling jacket. Nitration is a first-order reaction [14].

The mathematical model of the reactor is based on the standard equations of chemical kinetics and thermodynamics of chemical reactions [17]. The model has the following form

$$\begin{aligned}
&\frac{dx_1}{dt}=\left(u_1\cdot\rho_1+u_2\cdot\rho_2-k_0\cdot\sqrt{x_1\cdot\rho/S}\right)/\rho,\\
&\frac{d(x_1\cdot x_2)}{dt}=u_1\cdot C_1+u_2\cdot C_2-\\
&-k_0\cdot\sqrt{x_1/S}\cdot x_2-x_1\cdot k\cdot e^{-\frac{E}{R\cdot(273+x_3)}}\cdot x_2^n,\\
&\frac{d(x_1\cdot x_3)}{dt}=\\
&=\frac{u_1\cdot C_1\cdot\rho_1\cdot T_1+u_2\cdot C_2\cdot\rho_2\cdot T_2-k_0\cdot\sqrt{\frac{x_1}{S}}\cdot x_3\cdot c\cdot\rho}{c\cdot\rho}+\\
&+\frac{x_1\cdot k\cdot e^{-\frac{E}{R\cdot(273+x_3)}}\cdot x_2^n\cdot H-c_w\cdot u_3\cdot\rho_w\cdot(x_3-x_4)}{c\cdot\rho},\\
&\frac{dx_4}{dt}=\left(c_w\cdot u_3\cdot\rho_w\cdot(T_w-x_4)+S\cdot k_t\cdot(x_3-x_4)\right)/\left(c_w\cdot V_w\cdot\rho_w\right).
\end{aligned}\tag{1}$$

Table 1

Methods of research of objectives accomplishment in the design of precise control systems of nonlinear objects

Objective	Research method
1	Analytical development of a nonlinear model of dynamics of the vitamin B_6 synthesis reactor. Using the laws of mass action and chemical thermodynamics, the model is developed as a system of nonlinear differential equations. The order of the equations is defined by the order of the reaction occurring in a chemical reactor.
2	Approximation of the Colebrook-White nomogram. The research consists in considering the variation of the hydraulic friction coefficient (λ) with the fluid velocity. The variation of λ is caused by the nature of the control process, which involves different amounts of the control flow depending on the controller opening rate.
3	Analytical compilation of a model of the combined effect of the valve on the fluid flow in a pipeline, taking into account the flow velocity and λ, the linear or equal percentage flow characteristic of the valve.
4	Development of an analytical model of automation equipment, taking into account its characteristics, errors and dynamics. Dynamics is usually considered as the first-order, possibly delay, differential equation.
5	Analytical design of optimal multivariable controllers for the design of a precise control system of the vitamin B_6 synthesis reactor

The designations and nominal values of the model parameters are given in Table 2. The variables whose regime values are to be set are designated separately. These variables are $y_i=x_i$, i=1, 2, 3.

Table 2

Pyridone nitration parameters

Parameter	Specification	Nominal value	Unit
u_1	nitric acid flow rate	0.0028	m^3/s
u_2	pyridone suspension flow rate	0.0106	m^3/s
u_3	cooling water flow rate	0.012	m^3/s
x_1	reactor mixture volume	4.8	m^3
x_2	B_6 molar concentration	0.132	$kmol/m^3$
x_3	B_6 temperature	41	$kmol/m^3$
x_4	jacket water temperature	15	°C
F	B_6 flow rate	0.0152	m^3/s
C_1	HNO_3 molar concentration	0.61	$kmol/m^3$
C_2	pyridone molar concentration	0.129	$kmol/m^3$
T_1	HNO_3 temperature	20	°C
T_2	pyridone suspension temperature	41	°C
k	rate constant	$1.6\cdot10^{11}$	s^{-1}
E	activation energy	83.25	kJ/mol
R	universal gas constant	8.31	J/(mol·°C)
n	order of reaction	1	–
H	thermal effect of nitration	$1.5\cdot10^3$	J/mol
c	B_6 heat capacity	1,550	J/(kg·°C)
ρ	B_6 density	1,431	kg/m^3
c_1	HNO_3 heat capacity	1,744	J/(kg·°C)
ρ_1	HNO_3 density	1,400	kg/m^3
c_2	pyridone suspension heat capacity	1,529	J/(kg·°C)
ρ_2	pyridone suspension density	1,696	kg/m^3
S	heat transfer area	14.6	m^2
k_t	coefficient of heat transfer to water	947	$W/(m^2\cdot°C)$
V_w	jacket water volume	0.585	m^3
c_w	jacket water heat capacity	4,179	J/(kg·°C)
ρ_w	jacket water density	992.1	kg/m^3
T_w	inlet water temperature	8	°C

Let's standardize the model. To do this, we introduce the column vector g, containing the right members of DE of the system (1), and the matrix A, belonging to the DE left member. Then we get the model in the following form

$$dx/dt = A^{-1}\cdot g, \tag{2}$$

where

$$g^T = \begin{pmatrix} g_1 & g_2 & g_3 & g_4 \end{pmatrix},$$

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ x_2 & x_1 & 0 & 0 \\ x_3 & 0 & x_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A^{-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -x_2/x_1 & 1/x_1 & 0 & 0 \\ -x_3/x_1 & 0 & 1/x_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$g_1 = \left(u_1\cdot\rho_1 + u_2\cdot\rho_2 - k_0\cdot\sqrt{\frac{x_1}{S}}\cdot\rho \right) \Big/ \rho,$$

$$g_2 = u_1\cdot C_1 + u_2\cdot C_2 - k_0\cdot\sqrt{\frac{x_1}{S}}\cdot x_2 - x_1\cdot k\cdot e^{-\frac{E}{R\cdot(273+x_3)}}\cdot x_2^n, \tag{3}$$

$$g_3 = \frac{u_1\cdot C_1\cdot\rho_1\cdot T_1 + u_2\cdot C_2\cdot\rho_2\cdot T_2 - k_0\cdot\sqrt{\frac{x_1}{S}}\cdot x_3\cdot c\cdot\rho}{c\cdot\rho} +$$

$$+\frac{x_1\cdot k\cdot e^{-\frac{E}{R\cdot(273+x_3)}}\cdot x_2^n\cdot H - c_w\cdot u_3\cdot\rho_w\cdot(x_3-x_4)}{c\cdot\rho},$$

$$g_4 = \frac{c_w\cdot u_3\cdot\rho_w\cdot(T_w-x_4) + S\cdot k_t\cdot(x_3-x_4)}{c_w\cdot V_w\cdot\rho_w}.$$

Thus, the analytical nonlinear mathematical model of the dynamics of a control object has been developed.

5. 2. Development of a model of variation of the hydraulic friction coefficient

For calculation of hydraulic friction λ in round pipes under the flow rate variation, and, therefore, the Reynolds number, a special procedure was developed. It uses the current Reynolds number value (Re), and also the ratio of the pipeline inner diameter to the equivalent pipe roughness ($n_e=D/\Delta_{eq}$) as input parameters. The procedure body is an approximation of the well-known Colebrook-White nomogram for determining the coefficient of hydraulic friction λ, as well as the Stokes equation and approximation of the transient regime.

The developed model has the following form

$$\lambda = A + K\cdot\left(1 - e^{-t\cdot\frac{\lg(4000)}{T}}\right), \tag{4}$$

$$t = \lg(Re),$$

$$x = \lg(n_э),$$

where the coefficients of equation (4) are determined by the relationships (5)–(7)

$$T = 1{,}14\cdot10^{13}\cdot e^{-\left(\frac{x-56{,}5}{10{,}8}\right)^2} - 0{,}29\cdot e^{-\left(\frac{x-9{,}5}{2{,}1}\right)^2} +$$

$$+1{,}13\cdot e^{-\left(\frac{x-9{,}8}{3{,}8}\right)^2} + 0{,}15\cdot e^{-\left(\frac{x-6{,}2}{0{,}57}\right)^2}, \tag{5}$$

$$A = \frac{1{,}91\cdot10^4\cdot x^{-5{,}2} + 39}{1000}, \tag{6}$$

$$K = \frac{184{,}2\cdot x^{-0{,}26} - 131{,}7}{1000}. \tag{7}$$

The result of modeling for the function

$$\lambda = f\left(Re, D/\Delta_{eq}\right)$$

is shown in Fig. 1 and corresponds to the Colebrook-White nomogram [18].

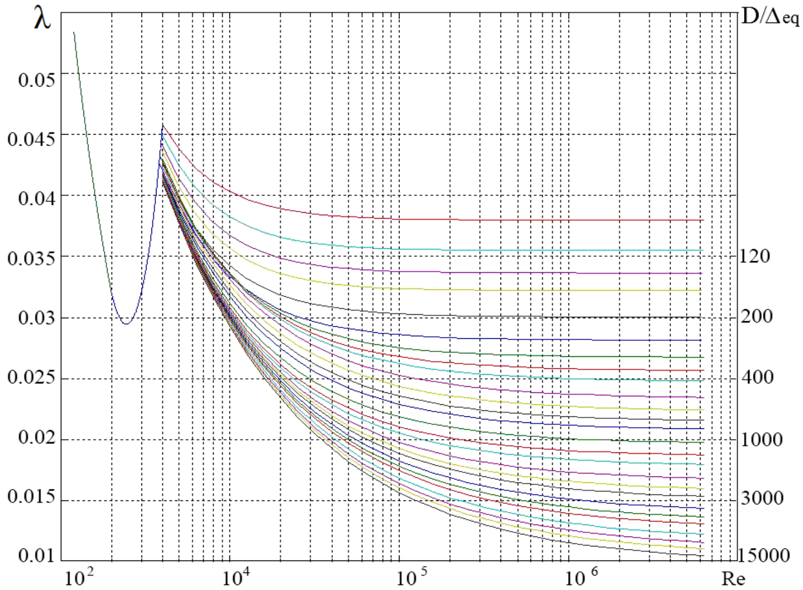


Fig. 1. The graph of $\lambda = f\left(\mathrm{Re}, D/\Delta_{eq}\right)$

The modeling revealed the difference of the linear and equal percentage flow characteristics of valves constructed using the variable λ from characteristics constructed using the averaged value λ. The variable λ was calculated from the approximation obtained.

5. 3. Development of a model of variation of the flow in the valve

The line pressure drop is determined by the expression [19]

$$\Delta P_L = \Delta P_M + \Delta P_P = \frac{\sum \xi \cdot \rho \cdot v^2}{2} + \frac{\rho \cdot L \cdot \lambda \cdot v^2}{2 \cdot D} = v^2 \cdot \alpha, \tag{8}$$

$$\alpha = 0{,}5 \cdot \left(\sum \xi \cdot \rho \cdot D + \rho \cdot L \cdot \lambda\right) / D, \tag{9}$$

where ΔP_M is the pressure drop in local resistances, Pa; ΔP_P is the pressure drop in straight pipeline sections, Pa; ξ is the local hydraulic drag coefficient; ρ is the flow density, kg/m^3; v is the flow velocity in the pipeline, m/s; L is the length of straight pipeline sections, m; λ is the hydraulic friction coefficient; D is the pipeline diameter, m; α is a coefficient.

The valve pressure drop

$$\Delta P_V = P_S - P_F + \Delta P_H - \Delta P_L = \beta - v^2 \cdot \alpha, \tag{10}$$

$$\beta = P_S - P_F + \Delta P_H, \tag{11}$$

where P_S is the initial pipeline pressure, Pa; P_F is the final pipeline pressure, Pa; ΔP_H is the hydrostatic pressure, Pa; ΔP_L is the line pressure drop, Pa; β is the auxiliary coefficient.

The hydraulic index is determined by the relationship:

$$n = \frac{\Delta P_L}{\Delta P_V} = \frac{v^2 \cdot \alpha}{\beta - v^2 \cdot \alpha} = \frac{1}{\gamma / Q^2 - 1}, \tag{12}$$

$$\gamma = \frac{\beta \cdot \pi^2 \cdot D^4}{16 \cdot \alpha}, \tag{13}$$

where γ is the auxiliary coefficient; Q is the volumetric flow rate of the medium, m^3/s.

It is known that for linear and equal percentage flow characteristics of the valve, the relative flow is determined from the expressions [19]

$$\mu = \frac{Q}{Q_{max}} = \sqrt{\frac{n+1}{n+1/S^2}} \tag{14}$$

and

$$\mu = \sqrt{\frac{n+1}{n+e^{2d(1-S)}}}, \tag{15}$$

where Q_{max} is the maximum flow of the medium through the valve for the assumed throughput capacity of the valve K_{vy}, m^3/s; S is the valve opening rate, (0<S<1); d is the flow characteristic shape factor, taken to be 3.91.

The maximum flow in the system will occur with a fully open valve:

$$Q_{max} = 3{,}2 \cdot \sqrt{\frac{\Delta P_G}{\rho}} \Bigg/ \sqrt{\left(\frac{1}{Kvy}\right)^2 + \left(\frac{1}{KvL}\right)^2}, \tag{16}$$

$$\Delta P_G = \Delta P_L + \Delta P_V, \tag{17}$$

$$K_{vL} = K_{vy} / \sqrt{n}, \tag{18}$$

where ΔP_G is the total drop in the system, Pa; K_{vl} is the line capacity.

Let us introduce the coefficient $K=1/S^2$ for the linear and $K=\exp(2 \cdot d \cdot (1-S))$ for the equal percentage flow characteristics and, after making the necessary transformations, we get:

$$\frac{Q^2}{Q_{max}^2} = \frac{\gamma / Q^2}{\gamma / Q^2 - 1 + K}. \tag{19}$$

By solving the biquadratic flow equation, we get

$$Q^4 \cdot (K-1) + Q^2 \cdot \gamma - Q_{max}^2 \cdot \gamma = 0,$$

$$D_i = \sqrt{K^2 \cdot \gamma^2 + 4 \cdot (K-1) \cdot Q_{max}^2 \cdot \gamma},$$

$$Q = \sqrt{\frac{-K \cdot \gamma + D_i}{2 \cdot (K-1)}}. \tag{20}$$

Thus, the model that allows considering the nonlinear relationship between the flow rate and the controller opening rate was obtained.

5. 4. Automation equipment modeling

For the implementation of the developed control system, the latest automation equipment with the field interface RS485 Modbus [20] is chosen and its models are developed. The technical structure of the developed control system is shown in Fig. 2.

The continuous reactor is equipped with temperature measuring sensors for measuring the temperature of the nitration process and the temperature of the jacket cooling water. The ultrasonic level sensors and concentration meter provide continuous measurement of the level and concentration of nitropyridone. The data on the measured parameters are input to the industrial computer, which implements the algorithm of the developed reactor control system. The controls are fed to the object input through the actuators Ram. Tek.L.3500 and controllers.

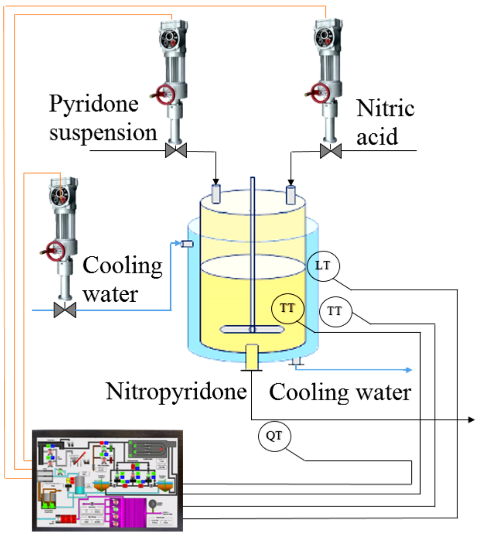


Fig. 2. Technical structure of the control system

The ultrasonic level sensor model has the following characteristics:

– the absolute measurement error is ±3 mm;

– the dynamics are represented by a lag element with a time constant of 0.2 s;

– the input signal is added to an evenly distributed stationary noise, the amplitude of which is equal to the error.

The concentration meter model has the following characteristics:

– the reduced measurement error is 2.5 %;

– the dynamics are represented by a lag element with a time constant of 0.5 s;

– the input signal is added to an evenly distributed stationary noise, the amplitude of which is equal to the absolute error.

The temperature transducer model has the following characteristics:

– the absolute error (0.15+0.002·t) °C;

– the dynamics are represented by a lag element with a time constant of 7.8 s;

– the input signal is added to an evenly distributed non-stationary noise, the amplitude of which is equal to the absolute error.

The controller model has the following characteristics:

– the dynamics are represented by a nonlinear instantaneous element;

– the error of simulation of conditional throughput capacity is 10 %.

The electric linear actuator model is developed proceeding from the fact that:

– the full speed time is 20 s;

– the run-down time is modeled by a time-lag element, where the lag is 0.04 s, and the time constant is 0.06 s;

– the backlash makes up 0.5 % of the speed;

– the limit of 1,200 switches per hour is introduced.

Thus, the models of the automation system equipment are developed and the technical structure of the automated control system of the vitamin B_6 synthesis reactor is proposed.

5. 5. Development of a precise control system of the vitamin B_6 production reactor

An object in the ACS is described by a system of nonlinear equations (1), supplemented by mathematical models of the equipment developed in section 5.4.

For the object control, a multivariable linear optimal digital controller with a model of step disturbances was chosen. The controller design is in accordance with the procedure described in [21, 22]. The model of the developed digital controller has the following form:

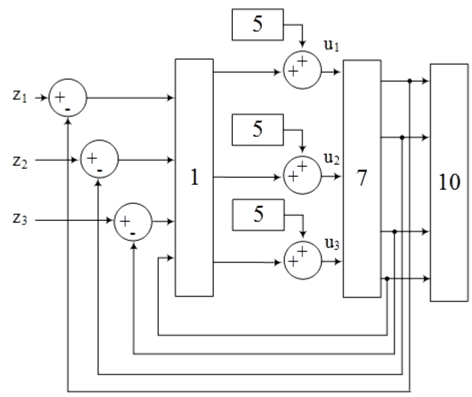
$$\chi_{i+1} = Ar \cdot \chi_i + Br \cdot (z_i - y_i), \quad (21)$$

$$u_i = Cr \cdot \chi_i, \quad (22)$$

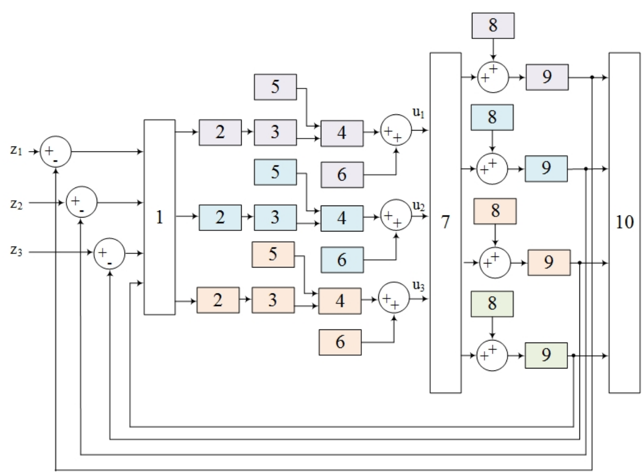
$$Ar \in \Re^{10,10},\ Br = \Re^{10,4},\ Cr = \Re^{3,10},$$

where z_1 is the level setting in the reactor; z_2 is the output product concentration setting; z_3 is the temperature setting in the reactor.

Block diagrams of models for a simplified and accurate modeling of the developed ACS of the vitamin B_6 production reactor are shown in Fig. 3, *a*, *b*.



a



b

Fig. 3. Block diagram of the control system modeling: *a* — simplified system; *b* — designed system; 1 — optimal multivariable controller; 2 — run-down actuator model; 3 — backlash actuator model; 4 — valve model; 5 — disturbance; 6 — uniform distributed random process simulating the control error; 7 — nonlinear model of the chemical reactor; 8 — uniform distributed random process simulating the sensor error; 9 — sensor model; 10 — system process logger

The transients obtained by modeling of the designed control system are shown in Fig. 4.

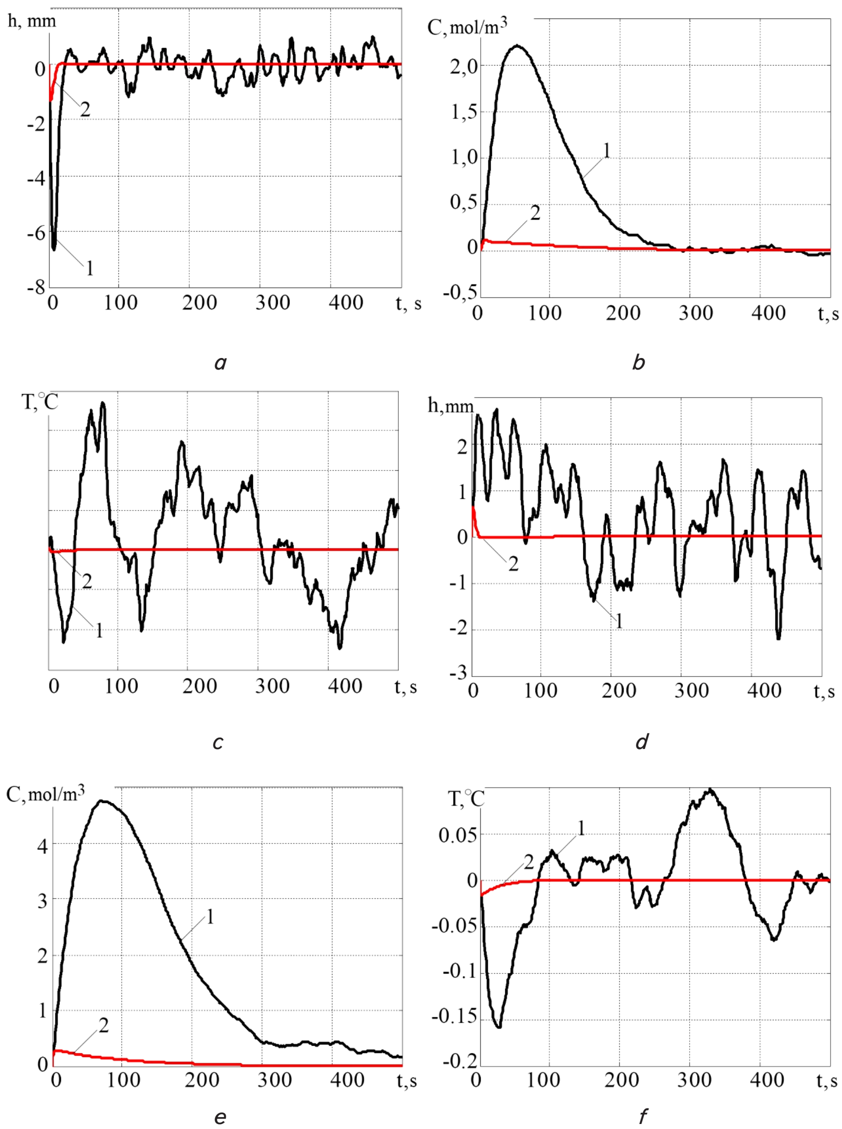


Fig. 4. Transients of parameter deviations: *a*–*c* – nitropyridone level, concentration, temperature at a 20 % pyridone suspension flow decrease; *d*–*f* – nitropyridone level, concentration, temperature at a 30 % nitric acid flow increase; 1 – designed control system; 2 – simplified control system

6. Discussion of the results of objectives accomplishment in the design of precise control systems of nonlinear objects

The approach to the design of precise control of industrial plants and math-ware for this approach in the form of a set of models are developed. Based on the approach, a precise automated control system of the vitamin B_6 synthesis reactor is developed. It can be seen that the characteristic feature of the proposed approach, which accounts for nonlinear properties of the ACS components, is getting more reliable results of modeling.

The analysis of the graphs in Fig. 4 shows that precise modeling of the automated control system yields the results that differ from the simplified system representation during the modeling. In addition to accurate simulation of the nonlinear model of the control object, accurate simulation of the real characteristics of the control equipment is also important in the design.

Despite the imperfection of the automation equipment, the designed precise ACS of the vitamin B_6 synthesis process ensures not only the high quality of the vitamin, but also the synthesis process safety.

The results of the research are recommended for use in the pharmaceutical and chemical industries for the synthetic production of vitamin B_6. Also, the results can be useful for the research organizations that are engaged in the design of digital precise control systems.

A certain drawback of the research is that the developed approach to the synthesis of precise control systems was applied only to the design of a precise control system of the vitamin B_6 production reactor. Further improvement of the above approach involves the design of precise control systems for other industrial plants.

7. Conclusions

1. The model of a pharmaceutical chemical reactor for vitamin B_6 synthesis, considering the mutual influence of the parameters, thermodynamics, kinetics and order of the chemical reaction in accordance with the standards for chemical reaction modeling is developed.

2. The model of the influence of the controller characteristics on the flow of control fluid, which is characterized by the accounting of the nonlinear relationship between the flow rate and the controller opening rate is developed.

3. The model of the variation of the hydraulic friction coefficient with the flow of the medium is developed. The model is based on the approximation of the Colebrook-White nomogram. A high degree of coincidence of the model with the original is shown. The advantage of the developed model of accounting for the variation of the hydraulic friction coefficient is the possibility of using it directly in the control process.

4. The model of automation equipment, the distinctive feature of which is the accounting for operating characteristics of real equipment such as error, inertia, lag, backlash, run-down and the number of switches is developed.

5. The precise automated control system of the vitamin B_6 synthesis reactor is developed. The multivariable optimal controller is designed. Due to small deviations of transients under the action of disturbances, the proposed precise automated control system ensures the high quality of the product and process safety in the reactor. The developed set of models was used in the controller design and modeling.

References

1. Stopakevich, A. A. Design of robust controllers for plants with large dead time [Text] / A. A. Stopakevich, A. A. Stopakevich // Eastern-European Journal of Enterprise Technologies. – 2016. – Vol. 1, Issue 2 (79). – P. 48–56. doi: 10.15587/1729-4061.2016.59107
2. Rutkovskii, V. Pretsizionnoe upravlenie nestatsionarnymi letatelnymi apparatami po uglu krena [Text] / V. Rutkovskii, V. Glumov, V. Suhanov // Problemy upravlenia. – 2011. – Issue 5. – P. 82–87.
3. Palamar, M. Doslidzhennia dynamichnyh pohibok sistemy pretsisijnogo keruvannia antenoyu z asinhronnym elektroprivodom [Text] / M. Palamar, Yu. Pasternak, A. Palamar // Visnyk Ternopolskogo natsionalnogo tehnichnogo universitetu. – 2014. – Vol. 76, Issue 4. – P. 164–173.
4. Zhu, W.-H. Precision Control of Modular Robot Manipulators: The VDC Approach With Embedded FPGA [Text] / W.-H. Zhu, T. Lamarche, E. Dupuis, D. Jameux, P. Barnard, G. Liu // IEEE Transactions on Robotics. – 2013. – Vol. 29, Issue 5. – P. 1162–1179. doi: 10.1109/tro.2013.2265631
5. Lei, L. Modeling and precision control of systems with hysteresis [Text] / L. Lei, Y. Yi. – UK, Oxford: Butterworth-Heinemann, 2015. – 178 p.
6. Seborg, D. E. Process dynamics and control [Text] / D. E. Seborg, T. F. Edgar, D. A. Mellichamp, F. J. Doyle. – USA, NJ, Holokn: John Willy and sons, 2011. – 514 p.
7. Prakash, J. Design of nonlinear PID controller and nonlinear model predictive controller for a continuous stirred tank reactor [Text] / J. Prakash, K. Srinivasan // ISA Transactions. – 2009. – Vol. 48, Issue 3. – P. 273–282. doi: 10.1016/j.isatra.2009.02.001
8. Shyamalagowri, M. Modeling and simulation of nonlinear process control reactor – continuous stirred tank reactor [Text] / M. Shyamalagowri, R. Rajeswari // International Journal of Advances in Engineering & Technology. – 2013. – Vol. 6, Issue 4. – P. 1813–1818.
9. Man, H. Nonlinear predictive adaptive controller for CSTR process [Text] / H. Man, C. Shao // Journal of Computational Information Systems. – 2012. – Vol. 8, Issue 22. – P. 9473–9479.
10. Shrivastava, P. Modeling and control of CSTR using model based neural network predictive control [Text] // P. Shrivastava // International Journal of Computer Science & Information Security. – 2012. – Vol. 10, Issue 7. – P. 38.
11. Suja Malar, R. M. Modeling of continuous stirred tank reactor using artificial intelligence techniques [Text] / R. M. Suja Malar, T. Thyagarajan // International Journal of Simulation Modelling. – 2009. – Vol. 8, Issue 3. – P. 145–155. doi: 10.2507/ijsimm08(3)2.128
12. Patrascioiu, C. Nonlinear dynamics of a hydraulic pressure control valve [Text] / C. Patrascioiu, M. Koester, A. Fidlin // 11th International Conference on Vibration Problems. – Lisbon, Portugal, 2013. – P. 129–135.
13. Patrascioiu, C. Control valves – modeling and simulation [Text] / C. Patrascioiu, C. Panaitescu, N. Paraschiv // CONTROL'09 5th WSEAS International Conference on Dynamical Systems and Control. – La Laguna, Spain, 2009. – P. 63–68.
14. Korotchenkova, N. Vitaminy geterotsiklicheskogo rjada. Strojenie, svojstva, sintez, himicheskaya tehnologia [Text] / N. Korotchenkova, V. Samarenko. – Sankt-Peterburg: SPHFA, 2006. – 80 p.
15. Obnovlenskiy, P. Sistemy zaschity potentsialno opasnyh protsessov himicheskoy tehnologii [Text] / P. Obnovlenskiy, L. Musiakov, A. Cheltsov. – Leningrad: Himia, 1978. – 257 p.
16. Remizova, O. Diagnostika potentsialno opasnyh sostijanij pri upravlenii tehnologicheskimi protsessami [Text] / O. Remizova, I. Rudakova, V. Syrikvashin, A. Fokin // Izvestija Sankt-Peterburgskogo gosudarstvennogo tehnologicheskogo instituta. – 2014. – Issue 25. – P. 88–94.
17. Kariakin, N. Osnovy himicheskoj termodinamiki [Text] / N. Kariakin. – Moscow: Akademia, 2003. – 463 p.
18. Rennels, D. C. Pipe Flow [Text] / D. C. Rennels, H. M. Hudson. – Hoboken, NJ: John Wiley & Sons, Inc., 2012. – 289 p. doi: 10.1002/9781118275276
19. Kaziner, Yu. Арматура систем автоматического управления [Text] / Yu. Kaziner, M. Slobodkin. – Moscow: Mashinostrojenie, 1977. – 136 p.
20. Liptak, B. G. Instrument Engineers' Handbook: Process control and optimization [Text] / B. G. Liptak. – USA, FL, Boca Raton: CRC Press, 2006. – 2304 p.
21. Stopakevych, A. Robust control system design of crude oil atmospheric distillation column [Text] / A. Stopakevych // Eastern-European Journal of Enterprise Technologies. – 2015. – Vol. 5, Issue 2 (77). – P. 49–57. doi: 10.15587/1729-4061.2015.50964
22. Stopakevych, A. Sistemnij analiz i teorija slozhnyh system upravlenija [Text] / A. Stopakevych. – Odessa: Astroprint, 2013. – 352 p.