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CREATION OF A SYSTEM FOR OPTIMAL CONTROL OF THE STATE OF PROCESS EQUIPMENT FOR PHOSPHORUS PRODUCTION

Abstract. The purpose of this work is to develop an intelligent system of optimal control of the technological process of yellow phosphorus production and a subsystem of operational diagnostics of the state of technological equipment. Methods of mathematical modelling, methods of experiment planning, methods of fuzzy modelling, methods of creation and training of neural networks and neural network algorithms were used in the course of research. On the basis of the performed research the following is proposed: a three-stage procedure for the development of intellectual or hybrid models of the object control process; synthesised intellectual model of optimal control of the process of electric smelting of phosphorite charge and investigated the intellectual models for adequacy, stability, unambiguity and sensitivity. The methodology of creation of subsystem of operative diagnostics of the state of process equipment as a part of ACSPP operating at NDFZ is offered.

Keywords: intelligent technology, neural networks, fuzzy logic, hybrid model, phosphate production, control system.

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Introduction. In the conditions of market economy the problem of development of methods and tools for creation of intellectual systems of optimal control of technological processes, which significantly increase economic efficiency, is urgent.

In our opinion, it is most effective to use intelligent technologies in combination with classical methods of process control. At the same time, it is possible to combine the advantages of traditional methods, technologies and algorithms with the mathematical apparatus of artificial intelligence theory. Such a system is called a hybrid control system.

We propose to test the developed methods and tools to create intelligent technologies for controlling the most complex technological process -

electrophosphorus smelting. After all, even a slight improvement in the performance of this process can lead to significant economic and environmental consequences. In addition to the requirements for high economic efficiency, attention is paid to the quality of products, which cannot be achieved without the use of management methods based on modern intelligent technologies.

Materials and methods. *Methodology for creating intelligent control systems.* The development of optimal process control model is understood as a chain of process model structure development → *Experimental research on the object → Model identification → Optimisation problem setting → Optimisation method selection → Development of optimal control algorithm.*

This traditional approach assumes that creating an optimal management system e is always a long, costly and successful way of doing things.

With the help of intelligent technologies, you can quickly solve such problems. The point is that artificial intelligence methods involve the use of knowledge, experience and intuition of human experts familiar with the subject area. In other words, the so-called 'ready knowledge' effect is used here. On the contrary, since the development of mathematical models, the main component of the system, is a process of generating 'new knowledge', theoretical research is time-consuming and experimental research and model identification are labour-intensive [1].

The transfer of "ready knowledge" from human experts to the knowledge base of intelligent systems greatly simplifies the creation of intelligent systems and simplifies their operation.

This paper proposes a three-stage procedure for creating an optimal process control system using the main idea of this research and the development of an accessible smart technology method.

At the first stage the a priori study of technical characteristics of the control object is carried out on the basis of literature sources, periodicals and factory technical documentation.

In the second step, a model of the management process is developed. With the help of experienced specialists, the basic control objectives (analogues of target functions in optimisation problems) are determined. The main task of the second stage is to compile a design matrix for a full factorial experiment (FFE). For example, using 2 input variables, the PFE design matrix shown in Table 1 can be generated.

Table 1

TFE planning matrix

No. of experiment	X_1	X_2	$Y^э$ expert judgement
1	0.0	0.0	
2	0.0	0.5	
…			
8	1.0	0.5	
9	1.0	1.0	

The values: 0.0; 0.5; 1.0 mean the minimum, average and maximum values of input variables X1 and X2. Experts can only set the value of the output variable in the range from 0.0 to 1.0 (control action), taking into account their own experience, knowledge and intuition.

Normalisation of input and output variables in the range from 0 to 1 is performed according to the following formula:

$$\bar{x} = \frac{x - x_{\min}}{x_{\max} - x_{\min}}, \quad (1)$$

where: $\bar{x}$ – normalised (from 0 to 1) value of the input or output variable; x – current value of the variable; x_{min}, x_{max} – minimum and maximum value of the variable.

The PFE design matrix can be used to create control models using four different methods: planning experiments, fuzzy algorithms, neural networks, neurofuji networks and hybrid models [2].

At the third stage, the created management model is investigated. The resulting model is scrutinised and analysed for sensitivity, stability and clarity. For this purpose, we simulate the management process with various changes in input variables, construct curves of changes in output variables as input variables change and analyse them with the involvement of experts.

After the study of the models obtained by different methods is completed, a comparative analysis of their validity is carried out.

The most suitable model should be simulation tested under current production conditions. At the same time, the actual input variables obtained from the measuring device of the industrial equipment are fed to the model input, and the modelling results (output control variables) are compared with the control values actually performed by experienced process operators.

For this purpose, the models are used to calculate output variables at the values of input variables taken from the PFE planning matrix and compared with the estimates given by the expert. After that, a comparison matrix is formed (see Table 2), which allows to calculate the magnitude of modelling error in different ways. For example, the absolute error in per cent is calculated by the formula:

$$\delta = 100\frac{1}{N}\sum_{i=1}^{N}|Y^{э} - Y^{p}| \quad (2)$$

where, $Y^{э}$ and Y^{p} – experimental and calculated values of output variables, respectively.

The absolute error is calculated for the models obtained by four different methods and then their comparative analysis is performed. The model with the lowest absolute error is considered to be the most adequate.

Specific features of yellow phosphorus production technology as a control object. The charge for electrophosphorus distillation consists of fillers, siliceous raw materials and coke from the glomerator plants, which are prepared in the drying and crushing departments. The charge for electrophosphorus distillation consists of the following components:

a) Sinter is the product of the calcination of the fine fraction of phosphorite in the sintering machine and is the main component of the charge, which contains phosphorus in the form of $Ca_3(PO_4)_2$;

b) Coke – coal coke with grain size 0.003-0.016 microns (3-16 mm) is dried at a moisture content of 1% or less and used as part of the charge for furnaces. Coke contains at least 83% carbon and plays the role of a phosphorus reducing agent in the electric distillation process. In order to obtain the required amount of coke, other reducing agents such as stoichiometric blast furnace coke, petroleum coke semi-coke can be used to reduce the content of P_2O_5 and impurities (Fe_2O_3, CO_2, H_2O, SO_2) contained in the raw material by 50, 75, 50 and 40 % respectively. To ensure the integrity of the reduction reaction, coke is introduced in quantities exceeding 3% of the stoichiometry.

If there is a shortage of reducing agents, phosphorus loss due to slag increases and the lining of the electric furnace is subjected to severe wear. An excess of reducing agent leads to an increase in the electrical conductivity of the charge, resulting in high electrode seating, upward displacement of the reaction zone, impeded slag release, increased furnace gas temperature, and so on;

c) Siliceous raw material – plays the role of flux in the charge and reduces its melting temperature. Phosphates with a high content of siliceous flux are used as siliceous raw materials, dried in such a way that the moisture content is 1% or less. The amount of flux introduced into the charge is determined by calculating the formation of slag with an acidity coefficient of 0.76-0.95 [3].

Excess or lack of flux in the charge leads to higher slag melting temperature, higher specific furnace power consumption and lower furnace productivity.

The process of phosphorus reduction is endothermic and takes place at a temperature of 1350-1500°C. The products of the process of yellow phosphorus production by reduction of phosphates with carbon in the presence of silica in the ore thermal furnace are furnace gases, slag and ferrophosphorus. Increasing the moisture content of the charge component leads to an increase in hydrogen content, loss of phosphorus, increase in the volume of furnace gases and additional energy consumption [4].

From the description of the phosphorus electro-melting technology, the following characteristics can be identified as a control objective:

– Significant inertia of the electromelting process due to the large volume of raw materials used;

– Large volume of silos and hoppers, resulting in significant delays in the respective control channels;

– Wide range of blast furnace components: Phosphite, fine agglomerate, fine quartzite, dust, coke;

– Uneven composition of charge components in ore hoppers.

On the one hand, the electric smelting process is not complicated in terms of charge preparation. The optimum charge composition is known from a pre-calculated charge calculation based on equilibrium equations. The charge enters the furnace when it is melted. The diversity of the electrothermal method is due to the fact that the products of the reduction reaction, namely gases containing phosphorus, slag consisting of calcium and magnesium silicates and pure phosphorus in the form of ferrophosphorus, condense from the gas and are obtained in pure form (99.5%) [5].

The main difficulties in the preparation of the wafers are caused by the disturbing effect of unregulated (but controlled) quantities of loading: fine flake fractions, coke, siliceous raw materials.

According to the formulation of this problem, the 3 – level hierarchical structure of the optimal control system of yellow phosphorus production will have the form shown in Figure 1.

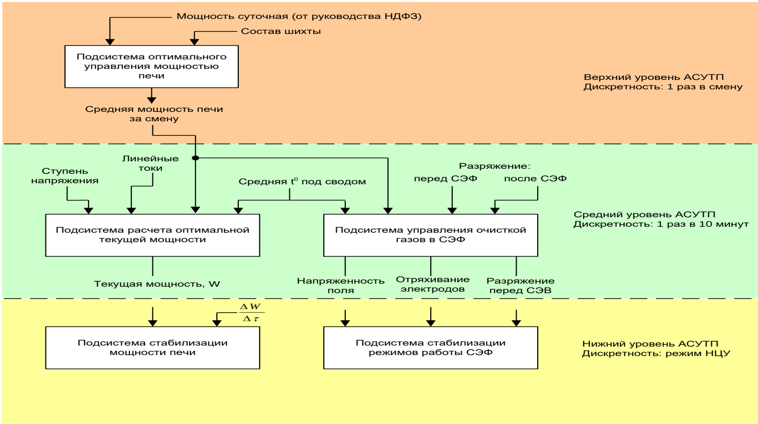

Fig. 1. Three-level hierarchical structure of the system of optimal control of the yellow phosphorus production process

At the top level of the control system, an intelligent subsystem calculates the optimal charge composition and furnace capacity for the current shift. Two subsystems operate at the middle level of the automated control system: a subsystem for calculating the optimal current capacity of the furnace and a subsystem for controlling the purification of furnace exhaust gases in dry electrostatic precipitators (ESPs). At the lower level of the automatic control system, the furnace power stabilisation system loads or raises the stabilisation electrodes, which stabilises the operating parameters of the furnace, which are calculated at the average level. Thus, the addition of a mid-level to the automatic control system allows the temperature under the furnace vault to be stabilised, resulting in reduced phosphorus losses due to off-gases after the condenser [6].

Research results and discussion. Formation of the design matrix for the full factor experiment. The main task in developing a control model is to formulate a design matrix for a Full Factor Experiment (FFE). The effectiveness of the entire control system depends on the quality of the FFE matrix. The FFE planning matrix should reflect the experience, knowledge and intuition of the technical specialists, i.e. the operators who work for a long time on the ore thermal phosphate furnace.

The table shows a fragment of the PFE planning matrix for four input and one output variable.

Table 2

TFE planning matrix for the middle management subsystem

Input variables					Output variable
No. of exp.	Voltage level, X_1	Linear currents, X_2	Crosshead height, X_3	Temperature under the vault, X_4	Current voltage, Y
1	0.0	0.5	0.0	0.5	0.76
2	0.5	0.5	0.0	0.5	0.53
3	1.0	0.5	0.0	0.5	0
…					
80	0.5	1.0	1.0	1	0.63
81	1.0	1.0	1.0	1	0.07

The PFE scheduling matrix can be used to develop control models in four ways: planning experiments, fuzzy modelling, neural network method and neurofuzzy method, depending on the temperature, voltage phase, linear value of flow rate and transverse height of electrodes under the furnace vault and current expertise in energy management.

Utilisation perspective. Development of an intelligent control model (algorithm). The intellectual model (algorithm) of controlling the process of yellow phosphorus production at the middle level of automatic control system was developed using three methods: fuzzy modelling, neural network method and neurofuji algorithm. The fuzzy model was developed using the graphical tool of Matlab system.

Comparative analysis of models for adequacy. We perform a comparative analysis of the adequacy of intelligent models and evaluate their sensitivity, visibility and stability. The results of the study of intelligent control models at the middle level of automated process control systems are summarised in the table below.

Table 3

Simulation results of intelligent models

No. of experimentation	Fuzzy logic	Neural network	Neuro-fuzzy network	Correct answer Y
1	0.76	0.76357	0.76	0.76
2	0.53	0.53443	0.53	0.53
. . .				
80	0.63	0.57944	0.63	0.63
81	0.07	0.064694	0.07	0.07
Error, %	0.3%	2.9%	0.2%	

The analysis of the table showed that the use of design of experiments is not possible due to unacceptably high values of absolute error. Intelligent models showed their advantages: from 0.2% to 2.9% the Neural Fuzzy Networks method was the best (0.2%).

Conclusion. Thus, the conducted research shows high efficiency of control algorithms obtained using artificial intelligence methods. Compared to classical methods of building analytical and statistical models, methods based on expert knowledge, experience and intuition provide optimal control systems for complex technological processes. At the same time, the assessment of reliability of intelligent models is an order of magnitude higher than in traditional modelling.

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ФОСФОР ӨНДІРУГЕ АРНАЛҒАН ТЕХНОЛОГИЯЛЫҚ ЖАБДЫҚТАРДЫҢ ЖАҒДАЙЫН ОҢТАЙЛЫ БАСҚАРУ ЖҮЙЕСІН ҚҰРУ

Аңдатпа. Бұл жұмыстың мақсаты сары фосфор өндірісінің технологиялық процесін оңтайлы басқарудың интеллектуалды жүйесін және технологиялық жабдықтың жай-күйін жедел диагностикалаудың ішкі жүйесін әзірлеу болып табылады. Зерттеу барысында математикалық модельдеу әдістері, экспериментті жоспарлау әдістері, анық емес модельдеу әдістері, нейрондық желілер мен нейрондық желі алгоритмдерін құру және оқыту әдістері қолданылды. Зерттеу негізінде: нысанды басқару процесінің интеллектуалды немесе гибридті модельдерін әзірлеудің үш сатылы процедурасы ұсынылған; фосфорит шихтасын электрмен балқыту процесін оңтайлы басқарудың интеллектуалды моделі синтезделді және зияткерлік модельдердің барабарлығына, тұрақтылығына, бірегейлігі мен сезімталдығына зерттеу жүргізілді. ҚҚҚҚ-ға әсер ететін АСУТП құрамындағы технологиялық жабдықтың жай-күйін жедел диагностикалаудың кіші жүйесін құру әдістемесі ұсынылды.

Тірек сөздер: интеллектуалды технологиялар, нейрондық желілер, бұлыңғыр логика, гибридті модель, фосфат өндірісі, басқару жүйесі.

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СОЗДАНИЕ СИСТЕМЫ ОПТИМАЛЬНОГО УПРАВЛЕНИЯ СОСТОЯНИЕМ ТЕХНОЛОГИЧЕСКОГО ОБОРУДОВАНИЯ ДЛЯ ПРОИЗВОДСТВА ФОСФОРА

Аннотация. Целью данной работы является разработка интеллектуальной системы оптимального управления технологическим процессом производства желтого фосфора и подсистемы оперативной диагностики состояния технологического оборудования. В ходе исследования использовались методы математического моделирования, методы планирования эксперимента, методы нечеткого моделирования, методы создания и обучения нейронных сетей и нейросетевых алгоритмов. На основе проведенного исследования предложена: трехэтапная процедура разработки интеллектуальных или гибридных моделей процесса управления объектом; синтезирована интеллектуальная модель оптимального управления процессом электроплавки фосфоритной шихты и проведено исследование интеллектуальных моделей на адекватность, устойчивость, однозначность и чувствительность. Предложена методология создания подсистемы оперативной диагностики состояния технологического оборудования в составе АСУТП, действующей на НДФЗ

Ключевые слова: интеллектуальные технологии, нейронные сети, нечеткая логика, гибридная модель, производство фосфатов, система управления.