SUMMARY
of the PhD Thesis
on the specialty 6D070200 – «Automation and Control»
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on the topic of research «Simulation and research of control system of phosphorite ore sintering process»

Topicality of the research. "Kazphosphate" LLP represents the phosphorus industry of the Kazakhstan Republic being the leading company in the production of phosphorus-containing products in the CIS countries. The company's products are supplied to the markets of Eastern and Western Europe, the CIS countries, China, as well as to the domestic market. The initial stage for the yellow phosphorus production, which is one of the important products of the company, is the sintering process.

Sintering is a non-linear process, which makes real-time quality control of the final product challenging. In practice, the process is controlled with a delay: the operator changes the process parameters after receiving the finished product, which leads to the appearance of a return – sinter, which must be returned to the initial stage for repeated processing. This circumstance leads to the appearance of a large number of returns, which are go through repeated processing. And although the waste in this case is minimal, the return leads to disturbances in the process and the need for additional costs for sintering. In this regard, to improve the product quality, it is necessary to conduct research on the process, the costs of which are reduced by creating a mathematical model. Also, control of the process until the sinter is obtained is an urgent task that can be resolved by predicting the quality of the product, which will make it possible to make a decision on control in advance.

The aim of the research consists in modeling the sintering process of phosphorite ores and developing a control structure. In this regard, it is necessary to determine the direction of modeling, the structure of the model, describe the developed mathematical models of physical phenomena, check for adequacy and accuracy. Based on the data obtained from the model, it is necessary to build a dynamic predictive model that will allow real-time prediction of the final product quality. To build a dynamic predictive model, it is necessary to analyze the existing models, determine its main parameters, build an optimal model, evaluate the accuracy and propose the structure of the control system based on the predictive model.

The main idea of the research. Based on the theory of heat transfer in porous media, develop a mathematical model based on physicochemical transformations occurring during sintering to conduct research on the sintering process and obtain sintering temperature curves for developing a prediction system. Develop an optimal dynamic model for predicting the burn through point based on a small volume of the initial sample and several variables, and propose a control structure based on the prediction.

Research objectives. In the dissertation work, the doctoral student set the following tasks:

– analyze mathematical models of the sintering process: main directions, modeling methods, used physicochemical processes and modeling tasks. Determine the most important features of mathematical models;

– develop a mathematical model of the sintering process and check its adequacy: describe the main physical and chemical processes, the modeling environment, present the research results;

– analyze predictive models of the sintering point: determine the main algorithms used for prediction, identify advantages and disadvantages, choose the optimal algorithm for building a prediction;

– develop a dynamic mathematical model for predicting the burn through point: check existing models for adequacy and accuracy, improve the accuracy of models by choosing the optimal size of the training initial sample, as well as using algorithms for finding the optimum;

develop the structure of the control system based on the predictive model and present the results.

The object of the research is the process of phosphorite ores sintering**.**

Methods of the research. The tasks were solved by carrying out theoretical and practical research. During the solving the set tasks, the laws of heat transfer in solid and gas, heat transfer in a porous material, laws of gas velocity, fuel combustion equations, correlation methods, various algorithms of the grey systems' theory, "swarm of particles" optimization algorithms, as well as theory and basic principles of sintering process were used.

Scientific outcomes. The scientific novelty of the research is as follows:

– a model of the sintering of phosphorite ores was developed based on the physics of heat transfer in porous media instead of classical heat transfer in solid and gas;

– a new optimal predictive grey model was developed, model based on continuous integral grey model and "particle swarm" optimization algorithm;

– on the basis of the developed optimal predictive grey model, an algorithm is proposed for obtaining a burn through point prediction of the sinter;

– a structure for control the sintering process is proposed, including the developed dynamic predictive model.

Statements of the defense:

1) a two-dimensional mathematical model of sintering in the COMSOL Multiphysics software has been developed based on the heat transfer in porous media, allowing to carry out research of the sintering process when the temperature inside the charge changes, changes in pressure, the content of fuel, water and other process parameters, as well as to carry out parametric analysis and optimization of the process taking into account real conditions and operating modes;

2) developed step-by-step algorithm for the optimal grey prediction model OGMC(1, n), based on the continuous integral grey convolution model GMC(1, n) and the "particle swarm" optimization method, which includes the determination of the influencing parameters, the size of the initial sample and the construction of the model itself;

3) developed dynamic gey predictive model of the sintering point of phosphorite ores, using one influencing parameter - gas velocity.

4) control structure based on a dynamic predictive model.

Practical significance of the research outcomes.

The practical significance of the developed mathematical model based on physical and chemical transformations is as follows:

– in the study of the sintering process: changing the composition, parametric analysis and solving optimization problems, performing mathematical experiments to improve the final product;

– the mathematical model can be used as a training platform (simulator) for sintering processes and the use of physics of heat transfer in porous materials.

The practical significance of the developed predictive model based on the grey systems theory is as follows:

– prediction of the burn through point of the sinter and synthesis of the control action based on the prediction;

– the algorithm for constructing a mathematical predictive model can be used for any process that has the character of a “grey exponential law”.

Practical contribution of the PhD student in obtaining scientific results is:

– formulation of research tasks and methods for their implementation;

– development and construction of a mathematical model describing the dynamics of the process through physical processes of heat transfer in porous media;

– development and construction of an optimal dynamic predictive model based on the theory of grey systems;

– development of the control system structure based on a dynamic predictive model.

Approbation of the thesis outcomes. The main results of the study were reported and discussed at the International Conferences: "Mathematical Methods and Information Technologies of Macroeconomic Analysis and Economic Policy", held in 2017 in Almaty, Kazakhstan; «The 16th International Scientific Conference Information Technologies and Management», held in 2018 in Riga, Latvia; «Integration of the Scientific Community to the Global Challenges of Our Time», held in 2019 in Sapporo, Japan; «International Conference on Control, Automation and Diagnosis (ICCAD)», held in 2019 in Grenoble, France.

Publications. According to the results of the study, 9 works were published. There are 4 papers at international conferences, one of which is in the world's largest technical professional organization for the advancement of technology IEEE, 3 papers in the journals of the HAC (highest atestation commission) list, 1 article was published in a foreign journal included in the international citation base Scopus and 1 article was published in the journal included in the JCR (Journal Citation Reports).

Volume and structure of the thesis. The thesis consists of an introduction, five sections of the main content, conclusion and appendices, a bibliography of 92 titles and contains 123 pages, 55 figures and 10 tables.

In the first section, the features of the technological process of sintering as a control object are considered and the direction for modeling the sintering process is

determined. The section provides an overview of various models of sintering, highlights their characteristic features, advantages and disadvantages. On the basis of a comparative analysis of the models, a further type of model of the sintering process, the main parameters and process variables, assumptions and limitations are determined.

In the second section, the object of modeling is presented, the basic equations describing the sintering process of the sintering are given, the properties and parameters of the model are determined. The physical properties of the processes that take place to obtain the sinter from the initial charge are described. Also, a direct model of the process is created and the results of modeling are presented.

The third section is devoted to assessing the current state of predictive models and their application, the existing models and methods of their construction are analyzed. Based on the analysis performed, the theory of grey systems was selected as a model for sintering.

The fourth section is devoted to the construction of a mathematical model for predicting the burn through point, starting from the determination of the main variables of the predictive model and ending with the construction of an optimal grey model. The subsections present various models of grey systems, as well as their use for the sintering process of phosphorite ores. As a result, a mathematical model for predicting the sintering point of an sinter based on the theory of grey systems was built, which allows obtaining high-accuracy results based on a small sample of data.

The fifth section is devoted to the description of the control system structure based on a dynamic prediction model, which will allow changing the process variables in real time in order to reach the burn through point of the sinter.

In the conclusion of the thesis, the main conclusions of the work are formulated based on the obtained results.

The appendix provides information about the initial data from the sinter workshop, presents algorithms for building predictive models and practical implementation of it.