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Analysis of physical and mechanical processes of flotation concentrate drying for automation control of drum drying furnace

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Abstract. The article shows that when analyzing the physical and mechanical processes of drying the flotation concentrate for the automation of the control of the drum drying furnace, it is important to take into account a number of features of the enrichment of non-ferrous metal ores, since non-ferrous metal ores are very diverse in their composition and properties. It is noted that based on the physical and mechanical properties of ores and in connection with their complex composition, small and fine dissemination of valuable components in non-ferrous metal ores, the main method of enriching these ores is flotation. The methods and materials of the article are based on the completed project for the construction of a pilot plant for filtration, drying and roasting of the product at a mining and metallurgical plant. The automation system under consideration uses modern technologies and high-performance equipment that fully meets not only the physical and mechanical processes of drying the flotation concentrate, but also all the necessary functional requirements. The presented results and discussion of the features of automation and control of the process of drying flotation concentrate in a drum drying oven take into account both current and future research needs and opportunities.

1 Introduction

Based on the classification of mineral processing methods, the analysis primarily focuses on physical, mechanical, and physicochemical processes that facilitate the separation of mineral raw materials into concentrate and waste [1-3]. The essence of physico-mechanical processes in the implementation of mineral processing and beneficiation technologies lies in the sequential concentration of valuable components into a commercial product. This commercial product can either be used directly as a finished product or serve as raw material for subsequent chemical and metallurgical processing.

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Concentration involves two main operations: the disintegration of extracted raw material into phases that differ in valuable component content, and the separation of these phases based on differences in their physical properties [4]. Clearly, in this context, the concentrate is a valuable product intended for further processing or use in other technologies. Its value is determined by the content of metals, organic matter, or chemical compounds.

It is worth noting that dehydration and drying are currently critical aspects of mineral processing from both technical and economic perspectives [5]. Automation and control of these operations aim to achieve optimal water/moisture removal with minimal energy consumption [6]. The effectiveness of automation largely depends on the technologies employed for raw material dehydration and drying. Consequently, several researchers have examined both the operations of technological processes (TP) and the characteristics of the raw materials and equipment used [7, 8].

It should be noted that existing dehydration and drying facilities are generally designed empirically, based on traditional technologies and experience in implementing such technological processes. Meanwhile, information on the latest developments, as well as the applied aspects and principles of efficient and sustainable design for dehydration and drying facilities, is scattered across various industry sectors. This fragmentation poses challenges for the integrated application of new knowledge [9].

Thus, the discussion of the features of automation and control of the physical drying process of flotation concentrate in a rotary drum dryer takes into account current and future research needs and opportunities. These are addressed by considering these processes from both industrial and physico-mechanical perspectives. The drying process of flotation concentrate in a rotary drum dryer and its automation features are considered in the context of improving the quality of flotation concentrate without compromising the recovery of valuable components from gold-bearing ores [10]. Study [11] presents a basic technological scheme for processing gold-bearing ores using flotation, highlighting reagent injection points for various technological operations. Study [7] outlines the drying technology for zinc and lead flotation concentrate, copper sludge, and washed kaolin. The authors report relatively better thermal characteristics, with significantly higher thermal efficiency of about 30-60%. In study [12], the principle of self-adaptive control based on data was applied in automating technological processes to address the instability of flotation processes, which causes fluctuations in the thickening-dehydration feed rate. It was found that the proposed control system can ensure the safe operating condition of equipment, optimize energy consumption, and provide the required operator comfort. In addition to control, the design of dehydration circuits (a combination of plant dehydration systems) is also critical for determining the overall performance of the system [13].

2 Materials and methods

The methods and materials are based on the development of a detailed working project for the construction of a pilot industrial facility (PIF) for the filtration, drying, and roasting of the product at a mining and metallurgical plant (MMP).

When analyzing the physico-mechanical processes involved in drying flotation concentrate for automating the control of a rotary drum dryer, it is essential to consider several characteristics of non-ferrous metal ore beneficiation [14]. Non-ferrous metal ores are highly diverse in their composition and properties. Industrial ore types are classified based on their chemical and mineral composition, oxidation level, textural and structural features, type of mineralization, as well as strength, crushability, and beneficiation potential. For instance, based on the content of the primary valuable components, ores are categorized as copper, copper-molybdenum, copper-nickel, copper-zinc, molybdenum, lead, polymetallic, tungsten, molybdenum-tungsten, and others.

Based on the ratio of the mineral forms of the primary metals, ores are categorized as follows:

- Sulfide ores: containing more than 80% sulfide minerals;
- Oxidized ores: containing less than 50% sulfide minerals;
- Mixed ores.

The majority of non-ferrous metals (80-85%) are found in sulfide ores. Ores containing more than 50% sulfides are classified as massive, while ores with less than 25% sulfides are referred to as disseminated ores. Based on the size of the mineralization, ores are categorized as coarse disseminated (with valuable component grain size d > 0.4 mm), medium disseminated (with d = 0.15÷0.4 mm), and fine disseminated (d < 0.15 mm).

Ores are considered soft if their strength coefficient on the M.M. Protodyakonov scale (f < 10), of medium hardness if f = 10÷14, hard if f = 14÷18, and very hard if f > 18 [15].

Based on the data of physico-mechanical properties and the complex composition, as well as the fine and very fine dissemination of valuable components in non-ferrous metal ores, the main method of beneficiation for these ores is flotation.

In the beneficiation of non-ferrous metal ores, more than 35 types of concentrates and products are obtained. The quality requirements for concentrates and products are regulated by standards and technical conditions. For example, copper concentrates of various grades must contain no less than 20-40% copper, with zinc impurities not exceeding 2-10% and lead impurities ranging from 2.5-8%. For zinc concentrates, the requirements are a minimum of 15-60% zinc, with impurities of iron not exceeding 4-18%, copper 0.9-11%, arsenic 0.05-9%, and silica 2-18%.

Some data on the metal content in ores and concentrates for the metallurgical industry are provided in Table 1.

Table 1. Percentage of metals in ores and concentrates.

Metal	Cu	Pb	Zn	Sn	Mo	W
Content in ore, %	0.4-2.0	1.3-3	2-4	0.3-1.0	0.1-0.5	0.05-0.3
Content in concentrate, %	5-40	40-73	45-56	45-60	45-51	50-65

Thus, the main elements of the technology for processing non-ferrous metal ores are physico-mechanical processes such as ore preparation, crushing and grinding, beneficiation, and dehydration of beneficiation products.

The analysis of the physico-mechanical processes involved in drying flotation concentrate is aimed at improving the efficiency of these processes through the automation of rotary drum dryer control. In considering this aspect, the following should be noted. To collect and process information and transmit it through the managed switch EDS-518A-SS-SC-T to the plant's automated control system, a Siemens SIMATIC S7-300 CPU 315-2 PN/DP controller is used. A communication processor, CP1, is also provided for communication, and it is utilized for visualization on the operator's panel.

The controller also includes a set of modules for receiving and transmitting analog and discrete signals:

- AI for monitoring the input analog parameters of the technological process;
- DI for monitoring discrete signals of equipment status;
- AO, DO for controlling technological equipment.

For the protection of the power supply system, uninterruptible power supply (UPS) units and power supply units (UZ) are used for the control and monitoring cabinet.

The human-machine interface is created using the SIMATIC WinCC Professional software package, which is installed on the operator workstations (APM).

The controllers used are programmed in the TIAPortal development environment, which allows for the configuration of modules within the controller and interface module, the development of software for the controller, and the creation of a technological process visualization system for the operator.

Thus, the system in question employs modern technologies and high-performance equipment that fully meets all necessary functional requirements [16].

3 Results and discussion

As part of the analysis of the physico-mechanical processes involved in drying flotation concentrate, let's consider the physical processes of flotation beneficiation. These are processes in which the separation of mineral particles is based on their selective adhesion to the interface of two phases. Depending on the phases involved, flotation can be foam, oil, hydrophobic solid surface, or fat surface flotation.

Foam flotation is a process that separates mineral particles in an aerated suspension based on differences in their wettability by water. Hydrophobic particles adhere to air bubbles and rise to form foam, while hydrophilic particles remain suspended in the liquid phase. The basic principle is as follows: the greater the contact angle of wetting, the stronger the adhesion of the mineral particle to the bubble. The contact angle for different minerals can vary widely. For example, it is around 0° for naturally hydrophilic quartz, 60-90° for coal, and 75-85° for sulfides.

The flotation properties of minerals, or their degree of wettability by water, can be artificially modified by treating their surface with flotation reagents. Depending on their purpose, flotation reagents are classified as follows.

Collectors are organic compounds that selectively act on the surface of specific mineral particles, reducing their wettability by water. Fatty acids, xanthates, and amines are commonly used as collectors.

Modifiers are chemical compounds that regulate the action of collectors. Activators enhance, while depressants weaken the action of collectors. Acids, bases, salts, and other compounds are used as modifiers.

Frothers are surfactants used to finely disperse air bubbles and form foam. Pine oil, pyrone alcohols, and terpineol are commonly used as frothers.

Auxiliary reagents include pH regulators, froth modifiers, flocculants, and dispersants.

Thus, the range of flotation reagents currently used for mineral flotation is very diverse, encompassing both organic and inorganic substances, natural products and synthetic compounds, as well as those that are highly soluble and practically insoluble in water.

The results of the development of the automation system and the discussion of the features of automation and control of the flotation concentrate drying process in the rotary drum dryer take into account, as mentioned above, both current and future research needs and opportunities. These are provided by considering these processes from an industrial perspective, utilizing SIMATIC S7-300 equipment in the automated control system, as well as the compact CPU 6ES7315-2EH14-0AB0 [17].

As noted by the developers of "Promenergo Avtomatika" this device belongs to the new family of Siemens microcontrollers designed to solve a wide range of low-level automation tasks. These controllers have a modular design and are versatile in their application. They are capable of operating in real-time, can be used to build relatively simple local automation nodes or nodes in complex automatic control systems that support intensive data communication through Industrial Ethernet/PROFINET networks, as well as Point-to-Point (PtP) connections [18].

The programmable controllers (PCs) of the S7-300 series have compact plastic housings with an IP20 protection rating, can be mounted on a standard 35 mm DIN rail or a mounting plate, and operate within a temperature range of 0 to +50°C. They are capable of servicing from 10 to 284 discrete channels and from 2 to 51 analog input/output channels. Communication modules (CM), signal modules (SM), and signal boards (SB) for discrete and analog signal input-output can be connected to the central processing unit (CPU) of the S7-300 programmable controller.

Based on the analysis of the documentation for the components from the manufacturer, specifically the company "Promenergo Avtomatika," for the SIMATIC S7-300 programmable controller, Table 2 presents selected options for analog/discrete input/output modules (SM) used in the automated control system for the filtration, drying, and roasting processes at the metallurgical plant.

Let us consider the features of the SIMATIC ET 200M distributed I/O system when applied in the automated control system (АСУ ТП). Notably, the interface module with enhanced features, IM 153-2 HIGH FEATURE for the ET 200M, supports up to 12 S7-300 modules, provides redundancy support, and includes time-stamping for isochronous mode, as well as special functions:

- 12 modules per station;
- Active SLAVE for switches and drives;
- Extended data for secondary HART variables;
- Operation with 64-channel modules;
- Extended time stamps with 32 signals per slot.

Table 2. Signal Modules (SM) and Their Features in the Automated Control System.

I/O modules	Features of use in automated process control systems
SM331 – individual signal input module for SIMATIC S7-300 PC	Fast conversion time. Possibility of connecting analog sensors without the use of intermediate amplifiers. High potential for solving complex management problems.
SM321 is a discrete input module for the SIMATIC S7-300 PC	Signal modules for increasing the number of discrete input channels handled by a single central processing unit (CPU) are designed for flexible adaptation of the controller to the requirements of the task at hand. They offer a high potential for the subsequent expansion of discrete input channels in existing automated control systems. This flexibility allows the system to scale as needed to accommodate additional inputs, ensuring that the automation system remains efficient and capable of meeting evolving operational demands.
SM322 is a discrete output module for the SIMATIC S7-300 PC	Signal modules are used to increase the number of discrete outputs handled by a single controller, providing flexible adaptation of the controller to the requirements of the task at hand. They enable the subsequent expansion of existing automation systems by adding additional sets of discrete output channels. This flexibility allows for scalable system growth without the need for complete reconfiguration, ensuring that the automation system can meet increasing operational demands effectively.

The support for redundancy in the system's interface components ensures the possibility of enhancing its operational reliability and minimizes potential data or control signal losses, as well as feedback. The features of the interface module for connecting the ET 200M station to the PROFIBUS DP network with electrical (RS 485) communication channels and performing the functions of a standard slave device are as follows. The IM 153-2 components can be used to connect ET 200M stations to redundant PROFIBUS DP networks, enabling the construction of distributed I/O systems with redundant SIMATIC S7-400H or SIMATIC

S7-400FH controllers. Additionally, it supports synchronization functions, time-stamping of telegrams, and clock synchronization functions.

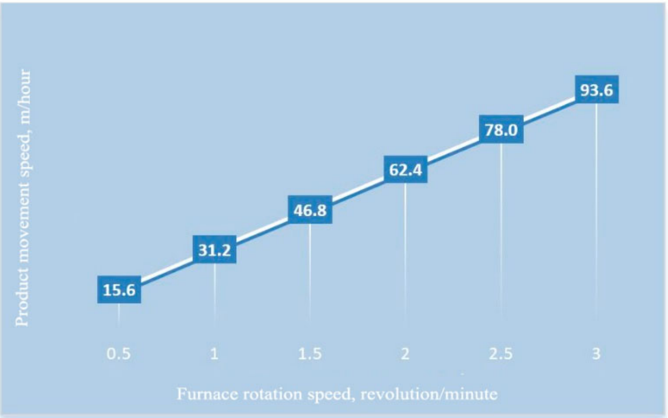
The analysis of the physico-mechanical processes of flotation concentrate drying for drum dryer automation allows for effective control over the parameters of the drying unit in order to enhance its performance. It should be noted that depending on the purpose, the same parameters are continuously monitored in some phases of production and periodically in others. The classification of a parameter as continuously or periodically monitored is somewhat conditional, as the nature of the process may cause a parameter to shift from one group to another.

Figure 1 shows a graph of the relationship between the product movement speed in the furnace and the furnace rotation speed, while Figure 2 presents a diagram depicting the furnace performance as a function of filling and rotation speed.

Under the control of object parameters in automation, it is understood as a set of actions aimed at stabilizing processes. In other words, the essence of control lies in the development of control decisions based on comparisons of the obtained results, which characterize the technological process, with the values of the technological map parameters (documentation). The regulating effect can be expressed by the following formula:

$$\rho_i = \rho_i T - \rho_i H > \alpha, \tag{1}$$

where $\rho_i T$ − current value;
$\rho_i H$ − set value;
α − permissible variation.



Graph of the dependence of product movement in the furnace on the furnace rotation speed

Fig. 1. Dependency of rotary drum dryer parameters: product movement speed as a function of furnace rotation speed.

For the practical implementation of control, it is necessary to:

- Select the control criterion;
- Obtain information on input and output values;
- Obtain information on the internal state of the system;
- Develop control and management algorithms (a set of mathematical operations performed in a specific order to solve control and management tasks);
- Equip the technological process with technical means.

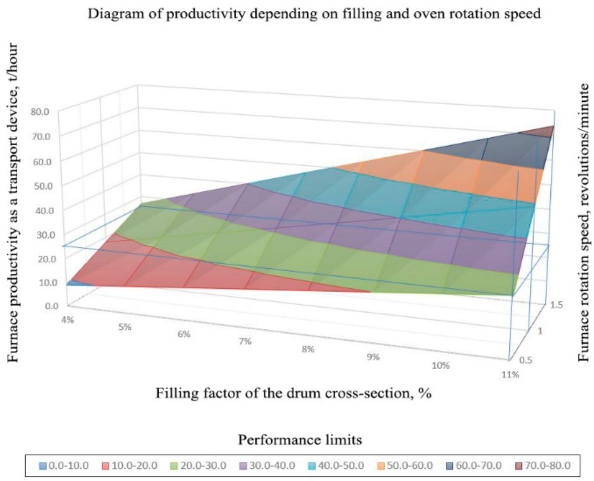


Fig. 2. Dependencies of furnace productivity on filling and rotation speed of the furnace.

When analyzing the physico-mechanical processes of flotation concentrate drying within the enrichment scheme, the most labor-intensive operation in automating drying units (including the drum drying furnace) is the measurement of the controlled parameter. It is primarily this process that determines the delay in obtaining information and, therefore, the effectiveness of regulation. As a result, the measurement time for the controlled parameter should be minimized, which can be achieved by using automated instrumental measurement methods, such as X-ray spectrometers, among others. In fact, the quality of production control depends on the reliability of the information obtained through measurement or parameter monitoring.

4 Conclusion

In conclusion, regarding the features of the physico-mechanical processes of flotation concentrate drying for the automation of drum dryer control discussed in the article, it should be noted that the composition of the hardware and software components of the Automated Control System (ACS) is based on modern technologies and high-performance equipment. This fully meets all the necessary functional requirements for the system and ensures full support for the principles of the Totally Integrated Automation concept. It is important to note that the implementation of this concept in process automation will achieve goals that are vital for the entire lifecycle of the ACS, aimed both at increasing productivity and reducing engineering costs in design and operation.

The system provides clear visualization of the physico-mechanical processes using input-output fields, graphs, curves, bar charts, textual information, and raster images. An important feature is the availability of graphic object libraries that simplify the development of the project. Centralized control of panel operation is provided to implement energy-saving algorithms based on the PROFIenergy protocol.

For the system's end users, key aspects include:

- low commissioning and maintenance costs; preservation/recovery of project data via PROFINET, USB, MPI, PROFIBUS DP interfaces, or using SIMATIC HMI SD cards;
- remote loading/reading of configuration parameters and the operating system with automatic process identification;

- the storage of archives and recipes in CSV file format, allowing standard computer applications to process them.

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