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Investigation of the effect of electro-hydraulic pulses on the combustion process of phosphorus sludge

The article considers the influence of electro-hydraulic pulses on the combustion of phosphorus sludge. Electric discharges in the environment of phosphorus sludge are sources of shock waves, which destroying the structure of phosphorus sludge and contribute to the intensification of the combustion process. A distinctive feature of the electro-hydraulic effect is the ability to control the parameters of pressure waves over a fairly wide range using the characteristics of the electric discharge circuit. For determine the optimal productivity and purity of the final product of the electric discharge unit's operation mode, experiments were conducted on the effect of the discharge energy on the efficiency of the electric discharge method for extracting phosphorus from phosphorus sludge. The efficiency of the electric discharge process was estimated by the amount of phosphorus that was released after settling and expressed as a percentage of the total amount of phosphorus in a phosphorus sludge's portion. The experiments were conducted out for sludges of different structures, with different phosphorus content and were conditionally divided into three groups: "rich" with phosphorus content — 70 %, "medium" — 50 % and "poor" — phosphorus content — 30 %.

Keywords: electro-hydraulic pulses, combustion, phosphorus, phosphorus sludge, electro-hydraulic effect, electric discharge, charging voltage, interelectrode gap, capacitor banks.

Introduction

Sludge containing elemental phosphorus should not be disposed of not only for economic reasons, but also for environmental reasons. As a result, at factories producing phosphorus, there is an acute question of developing effective methods and means for processing sludge in order to eliminate the loss of a valuable product. The most perspective method is to burning them in furnaces with a special design, thus obtaining slime phosphoric acid in one stage of processing, which quality depends on the structure of burned phosphoric sludge.

The combustion reaction is a chemical reaction in which atoms from molecules of substances (fuel) are combined with an oxidizer (usually air oxygen) toformcombustion products. An example of a combustion reaction is the interaction of phosphorus with oxygen, which is provided by the equation:

$$4P + 3O_2 \rightarrow 2P_2O_3\ (P_4O_6) \quad \text{(when a lack of oxygen);}$$

$$4P + 5O_2 \rightarrow 2P_2O_5\ (P_4O_{10}) \quad \text{(with an excess of oxygen).}$$

Here are the stoichiometric coefficients 4, 3, 2, 5 that denote the number of moles oxygen and phosphorus that participate in the combustion reaction of one mole of propane. Similar equations are used to describe molecular transformations, which are elementary stages (reactions) of a chemical process [1].

Elementary reactions correspond to real molecular events.

Phosphorus, which is a part of combustible substances of organic and mineral origin, oxidizes during combustion and forms phosphoric anhydride (P_2O_5). Phosphorus anhydride P_2O_5 (tetraphosphordecaoxide) is produced from the combustion of phosphorus under conditions of free access of air.

Experimental

The combustion process of phosphorus and phosphoric sludge is considered in a number of works [2, 3]. However, in these works, the electrophysical aspects of the combustion process of phosphorus and phosphorus sludge were not affected, and not in all works examined the effect of the concentration of impurities on the intensity of the combustion process.

Combustion is usually understood as a rapid physical and chemical redox process with the release of a large amount of heat, which is capable of self-propagation and often accompanied by a glow and the formation of a flame. A specific feature of combustion is the presence of electrophysical phenomena observed during the occurrence and development of the flame, associated with the appearance of a spatial distribution of charges in the flame. The consequence of this distribution is the existence of its own electric field, which is absent in ordinary plasma.

The effect of an earlier appearance of charged particles in comparison with a significant increase in temperature caused by non-equilibrium chemical reactions occurring during the period of self-ignition was found in the works. This effect was detected by using the probe method. The essence of this method is that a metal probe is introduced into the investigated point of the flame and the current-voltage characteristic is taken [4].

Results and Discussion

To study the thermophysical and electrophysical aspects of combustion, phosphorus sludge in the form of tablets with a diameter of 5 mm was placed in a cylindrical quartz glass reactor. For the manufacture of phosphorus sludge samples, were used several types of initial products. The first is pure phosphorus, the second is a sludge with a high phosphorus content (about 80 %), which is an emulsion of water in phosphorus, the third sludge with an average phosphorus content (about 50 %), which is an emulsification suspension of phosphorus in water, and the fourth sludge with a low phosphorus content (approx. 30 %) which is also an emulsification suspension of phosphorus in water. The temperature was measured through a chromel-copel thermocouple. The measurement procedure was consisted of heating and self-igniting sample in the reactor, recording the temperature and emerging electric potential.

Figure 1 shows the characteristic signals from the thermocouple and probe received by combustion the sludge tablet. The following main stages of burning are clearly visible on the graph: combustion; 1 — drop heating, water evaporation; 2 — pre-ignition stage; 3 — separation of volatile components of the mineral part of the sludge, as well as particles of the armor shell of phosphorus drops (in the sludge); 4 — the stage of stable combustion.

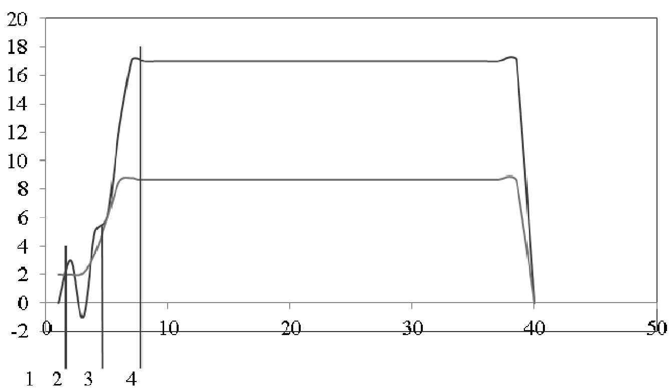


Figure 1. Characteristic signals from the thermocouple and probe

In the process of heating and combustion tablets of phosphorus sludge in the reactor volume is observed the so-called intra-furnace crushing of phosphorus droplets. This phenomenon was named microexplosion. The microexplosion is explained by the difference in the boiling points of water (t_w = 100 ºC) located inside the samples and phosphorus (t_{ph} = 280 C). The intra-furnace crushing of drops of phosphorus sludge emulsion not only increases the combustion surface, but also improves the mixture formation of phosphorus vapors with air. This in turn reduces the combustion time.

The effect of an earlier appearance of charged particles in comparison with a significant increase in temperature was detected, due to nonequilibrium chemical reactions occurring during the self-ignition period (stage 2 in Figure 1). This effect is expressed by recording the peak of the signal from the probe in the pre-ignition stage, which makes it possible to accurately record the moment of the beginning of the phosphorus combustion process in phosphorus sludge, and therefore, with a sufficient degree of accuracy, measure the combustion time of a certain sample of the burnt substance

The combustion of dispersed fuel systems (suspensions and emulsions) sprayed in a gaseous oxidizer stream in terms of basic characteristics significantly differs from the combustion of natural fuels (solid or liquid). Dispersed fuel systems based on widely used natural fuels are essentially new energy fuels, which in some cases are characterized by higher combustion rates than the initial. In the process of combustion a drop of phosphorus sludge when sprayed with nozzles during the evaporation of water and the emission of volatile (phosphorus vapors) in the droplet of the emulsion or emulsification, the intra-volume surface strongly develops. As a result, there is intra-porous oxidation of the sludge with explosive evolution and combustion of phosphorus vapor. The internal volume of the reaction surface is determined by the degree of dispersion of phosphorus particles in the emulsification suspension, as well as by the presence of an “armor” shell of phosphorus droplets [5].

Electric discharges in the environment of phosphorus sludge are sources of shock waves, which destroying the structure of phosphorus sludge and contribute to the intensification of the combustion process. During the passage of shock waves and compression waves, happens the destroying of the shell of the phosphorus droplets, the particles of the solid stabilizer break off from the phosphorus-water interface, but along with this, since phosphorus droplets are relatively easily deformable, due to the high pressure at the front of the shock wave, a dispersion process of phosphorus particles is possible. A distinctive feature of the electro-hydraulic effect is the ability to control the parameters of pressure waves over a fairly wide range (hydrodynamic characteristics of the discharge) using the characteristics of the electric discharge circuit (such as capacitance of capacitor banks, discharge voltage). In turn, the parameters of the shock wave, which is the main tool for influencing the structure of phosphorus sludge, make it possible to control the dispersion of phosphorus particles, thereby affecting the combustion process of atomized drops of phosphorus sludge [6].

Electro-hydraulic pulses, by destroying the structure of phosphorus sludge, contribute to the formation of “centers” with a higher content of phosphorus, free from the shell of mineral and organic impurities. The formation of “centers” with a high concentration of phosphorus can be effectively used in the burning of sludge to obtain thermal phosphoric acid. The aforementioned “centers” in this case can play the role of combustion centers. The intensification of combustion also contributes to the dispersion of phosphorus particles in the phosphorus sludge.

Next, experiments were carried out to measure the combustion time of samples of phosphorus sludge with different phosphorus contents: “rich” — 70 %, “medium” — 50 %, “poor” — 30 % phosphorus after processing electric discharges of various capacities. The discharge energy was regulated by the value of the initial voltage U_0, the capacitance of capacitor banks C, and the value of the working interelectrode gap l_{dg}.

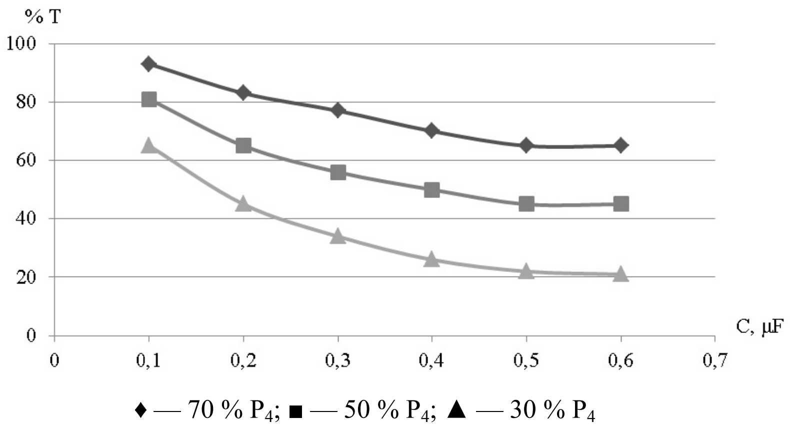
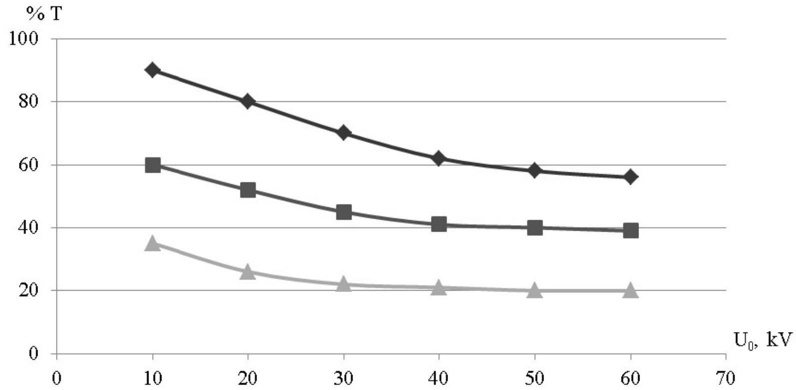


Figure 2. Dependence of the phosphorus combustion time on the capacity of the discharge circuit capacitor banks

Figure 2 shows the results of measurements of the combustion time of sludge tablets with different contents of P_4 depending on the capacitance of capacitor banks C. The initial voltage U_0 was 30 kV, and the interelectrode gap was l_{dg} = 12 mm.

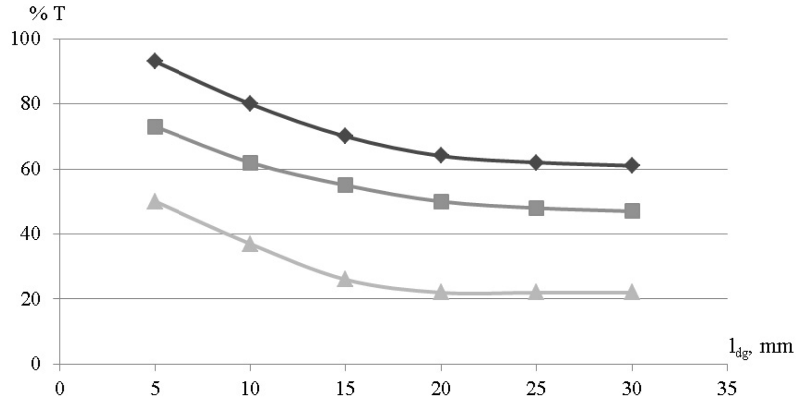
Next, Figure 3 shows the dependence of the combustion time on the initial voltage U_0 of the generator at the capacitance of the capacitors C = 0.25 μF, the interelectrode distance l_{dg} = 12 mm.



♦ — 70 % P_4; ■ — 50 % P_4; ▲ — 30 % P_4

Figure 3. Dependence of the combustion time on the initial voltage of the generator

The third series of experiments on measuring the combustion time was carried out at the initial voltage U_0 = 30 kV, the capacity C = 0.25 μF, the interelectrode distance l_{dg} varied from 5 mm to 30 mm. The results are shown in Figure 4.



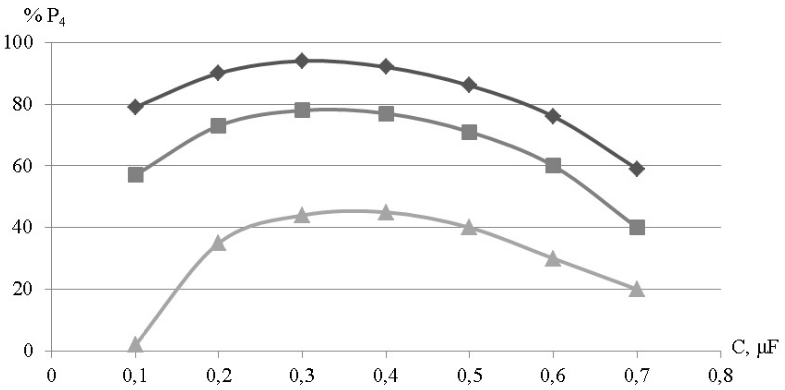
♦ — 70 % P_4; ■ — 50 % P_4; ▲ — 30 % P_4

Figure 4. Dependence of the combustion time on the value of the interelectrode gap

In order to determine the optimal productivity and purity of the final product of the electric discharge unit's operation mode (to intensify the mass transfer of phosphorus), experiments were conducted on the effect of the discharge energy on the efficiency of the electric discharge method for extracting phosphorus from phosphorus sludge. The efficiency of the ED process was estimated by the amount of phosphorus that was released after settling and expressed as a percentage of the total amount of phosphorus in a phosphorus sludge's portion, previously determined by the results of iodometric chemical analysis.

The experiments were conducted out for sludgesof different structures, with different phosphorus content and were conditionally divided into 3 groups: "rich" with phosphorus content — 70 %, "medium" — 50 % and "poor" — phosphorus content — 30 %.

In Figure 5 shows the experimental results of the study of the ED treatment efficiency for various sludges depending on the capacity of capacitor banks.

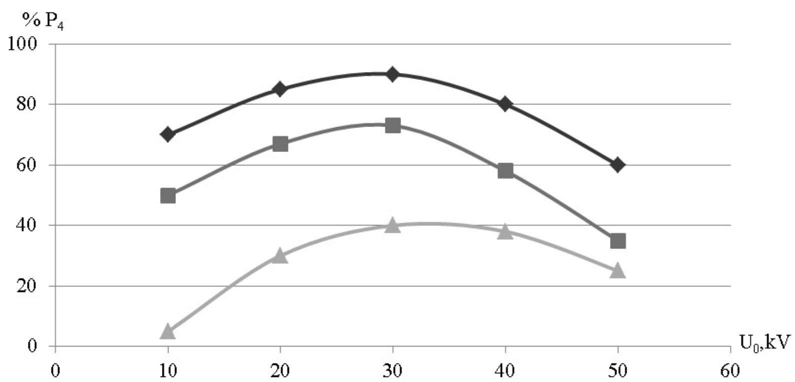


♦ — 70 % P_4; ■ — 50 % P_4; ▲ — 30 % P_4

Figure 5. Dependence of the degree of phosphorus extraction on the capacity of capacitor banks

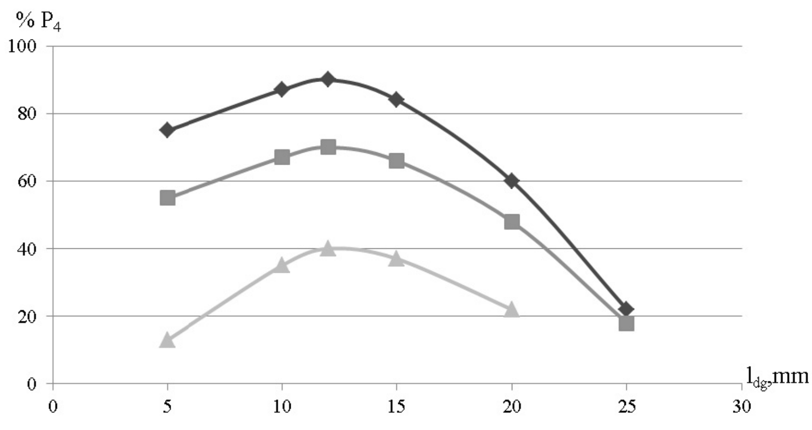
With a constant charging voltage of the ED pulse generator of 30 kV and the value of the interelectrode gap of 10 mm, the capacity varied within C = 0.1–0.5 μF. The dependence is extreme and the maximum value of the amount of phosphorus released is observed when the capacity of the capacitor bank is 0.25 μF. ♦ — 70 % P_4; ■ — 50 % P_4; ▲ — 30 % P_4.

Further, Figure 6 shows the results of similar experiments for the case of variation of the initial voltage U_0 in the range of 10–50 kV, while the capacity C = 0.3 μF, the value of the interelectrode distance l_{dg} is 10 mm. The maximum effect is observed at U_0 = 30 kV.



♦ — 70 % P_4; ■ — 50 % P_4; ▲ — 30 % P_4

Figure 6. Dependence of the degree of phosphorus extraction on the charging voltage



♦ — 70 % P_4; ■ — 50 % P_4; ▲ — 30 % P_4

Figure 7. Dependence of the degree of phosphorus extraction on the value of the interelectrode distance

The third series of experiments was conducted with the following parameters of the discharge circuit U_0 = 30 kV, C = 0.25 μF. The value of the interelectrode gap varied within the range of l_{dg} = 5–25 mm. The results are shown in Figure 7 the maximum efficiency of the process was observed at l_{dg} = 12 mm.

Conclusions

We note that according to the results of laboratory experiments, the intensification of burning of phosphoric sludge is observed at the following parameters of an electric discharge installation — the initial voltage U_0 = 35 kV, the capacitance of capacitors C = 0,4 μF, the interelectrode distance l_{dg} = 12 mm. These results were used further in determining the parameters of the discharge circuit of a pilot plant for processing phosphoric sludge into phosphoric acid.

Based on the results of laboratory technological experiments, we can make the following conclusion. The maximum effect of using electric discharges to extract phosphorus from phosphorous sludge is observed at the following parameters of the discharge circuit of the high-voltage pulse generator: U_0 = 30 kV, C = 0.3 μF, l_{dg} = 12 mm.

The presence of maxima on the above dependencies is explained by the fact that when the pulse energy determined by the charging voltage, the capacitance of the capacitors, and the value of the interelectrode gap is less than the threshold, the extraction effect is not observed, since the pulse energy insufficient to destroy the structure of the emulsion. In addition, at a very high pulse energy, the effect of dispersion of phosphorus particles in the emulsion is observed and it becomes sedimentally and aggregatively stable.

References

1 Вильямс Ф.А. Теория горения / Ф.А. Вильямс. — М.: Наука, 2001. — 615 с.

2 Исламов М.Ш. Печи химической промышленности. — 2-е изд. / М.Ш. Исламов. — М.: Химия, 1975. — 432 с.

3 Бернадинер М.Н. Огневая переработка и обезвреживание промышленных отходов / М.Н. Бернадинер, А.П. Шурыгин. — М.: Химия, 1990. — 304 с.

4 Миронов В.Л. Основы сканирующей зондовой микроскопии: учеб. пос. для студ. ст. курсов высш. учеб. завед. — Нижний Новгород: РАН; Ин-т физики микроструктур, 2004. — 110 с.

5 Андронов В.И. Термическая фосфорная кислота, соли и удобрения на ее основе / В.И. Андронов, А.А. Бродский, Ю.А. Забелешинский. — М.: Химия, 1976. — 205 с.

6 Дормешкин О.Б. Исследование процесса гидравлической классификации фосфорного шлама с целью извлечения фосфора для производства глифосата / О.Б. Дормешкин, Г.С. Кенжибаева, С.С. Шалатаев, К.Т. Жантасов, Ш.К. Шапалов, Д.М. Жантасова // Изв. НАН РК. Сер. хим. и технол. — 2017. — № 6(426). — С. 97–102.

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Электрогидравликалық импульстардың фосфор шламының жану процесіне әсерін зерттеу

Мақалада электрогидравликалық импульстардың фосфор шламының жану процесіне әсері қарастырылған. Фосфорлық шламды ортадағы электрлік разрядтар фосфор шламының құрылымын бұзатын және жану процесінің күшеюіне ықпал ететін соққы толқындарының көзі. Электрогидравликалық әсердің ерекшелігі электрлік разряд тізбегінің сипаттамаларын қолдана отырып, қысым толқындарының параметрлерін жеткілікті кең ауқымда реттеу мүмкіндігі. Соңғы өнімнің өнімділігі мен тазалығы бойынша оңтайлы электроразрядты қондырғының жұмыс режимін анықтау үшін разряд энергиясының фосфор шламынан фосфорды алудың электроразрядты әдісінің тиімділігіне әсері бойынша тәжірибелер жүргізілді. Электроразряд процесінің тиімділігі тұндырудан кейін бөлінген фосфор мөлшерімен бағаланды және фосфор шламының құрамындағы фосфордың жалпы мөлшерінің пайызымен көрсетілді. Тәжірибелер әр түрлі құрылымдағы, құрамында фосфор мөлшері әр түрлі және шартты түрде үш топқа бөлінген үлгілер үшін жүргізілді: бар құрамында фосфор «мол» —70 %, «орташа» — 50 % және құрамында фосфор «аз» —30 %.

Кілт сөздер: электрогидравликалық импульстар, жану, фосфор, фосфор шламы, электрогидравликалық әсер, электр разряды, зарядтау кернеуі, лектрод аралық қашықтық, конденсаторлық батареялар.

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Исследование влияния электрогидравлических импульсов на процесс горения фосфорного шлама

В статье рассмотрено влияние электрогидравлических импульсов на процесс горения фосфорного шлама. Электрические разряды в среде фосфорного шлама являются источниками ударных волн, которые разрушают структуру фосфорного шлама и способствуют интенсификации процесса горения. Отличительной особенностью электрогидравлического эффекта является возможность с помощью характеристик электроразрядного контура регулировать параметры волн давления в довольно широких пределах. Для определения оптимального по производительности и чистоте конечного продукта режима работы электроразрядной установки были проведены опыты по влиянию энергии разряда на эффективность электроразрядного способа извлечения фосфора из фосфорного шлама. Эффективность электроразрядного процесса оценивалась количеством выделившегося фосфора после отстаивания и выражалась в процентах от общего количества фосфора в навеске фосфорного шлама. Опыты проводились для шламов различной структуры, с различным содержанием фосфора и условно разделенной на три группы: «богатый» с содержанием фосфора — 70 %, «средний» — 50 и «бедный» — содержание фосфора — 30 %.

Ключевые слова: электрогидравлические импульсы, горение, фосфор, фосфорный шлам, электрогидравлический эффект, электрический разряд, зарядное напряжение, межэлектродный зазор, конденсаторные батареи.

References

1 Williams, F.A. (2001). *Teoriia horeniia [Theory of combustion]*. Moscow: Nauka [in Russian].

2 Islamov, M. Sh. (1975). *Pechi khimicheskoi promyshlennosti [Furnaces of chemical industry]*. (2nd ed.). Moscow: Khimiia [in Russian].

3 Bernadiner, M.N., & Shurygin, M.N. (1990). *Ohnevaia pererabotka i obezvrezhivanie promyshlennykh otkhodov [Fire processing and neutralization of industrial waste]*. Moscow: Khimiia [in Russian].

4 Mironov, V.L. (2004). *Osnovy skaniruiushchei zondovoi mikroskopii [Fundamentals of scanning probe microscopy]*. Nizhny Novgorod: RAS; Institute of microstructure physics [in Russian].

5 Andronov, V.I., Brodsky, A.A., & Zabeleshinsky, Yu.A. (1976). *Termicheskaia fosfornaia kislota, soli i udobreniia na ee osnove [Thermal phosphoric acid, salts and fertilizers based on it]*. Moscow: Khimiia [in Russian].

6 Dormeshkin, O.B., Kenzhibayeva, G.S., Shalataev, S.S., Zhantasov, K.T., Shapalov, Sh.K., & Zhantasova, D.M. (2017). Issledovanie protsessa hidravlicheskoi klassifikatsii fosfornoho shlama s tseliu izvlecheniia fosfora dlia proizvodstva hlifosata [Investigation of the process of hydraulic classification of phosphorus slime to obtain the phosphorus for the production of glyphosates]. *Izvestiia Natsionalnoi akademii nauk Respubliki Kazakhstan. Seriia khimii i tekhnolohii — News of the National academy of sciences of the Republic of Kazakhstan. Series chemistry and technology*, *6(426)*, 97–102 [in Russian].