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Research Article

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Dehydration and Environmentally Friendly Thermal Processing of Excess Activated Sludge

Regina Ya. Iskhakova ✉, **Artur I. Nurgaliev**
Kazan State Power Engineering University, Kazan, Russian Federation
✉ imreginaiskh@gmail.com

Abstract
Introduction. Currently, there is a problem with the accumulation of large amounts of production waste. One type of this waste is excess activated sludge, which is a waste product from biological wastewater treatment that has a high moisture content. When excess activated sludge is deposited in beds, problems can arise related to changes in the gas-air environment, the release of unpleasant odors, as well as the contamination of groundwater and soil. Prolonged presence of sediment in sludge beds in oxygen-free conditions leads to its decay and deterioration of moisture-yielding properties. For these reasons, the development of new methods for disposing of large volumes of waste generated during wastewater treatment is essential. The aim of this research is to develop a technique for preliminary neutralization and thermal treatment of excess activated sludge using energy waste.
Materials and Methods. The work used excess activated sludge with a moisture content of 98.2% (waste of hazard class IV). Water treatment sludge (waste of hazard class V) was used as a reagent to increase moisture yield. For experimental studies on dehydration, a laboratory centrifuge Elmi CM-6M.01 was used. Tests were conducted under various conditions (500, 1,000, and 1,500 revolutions per second for 1, 2, and 3 minutes), and the value of centrifugation was determined as a criterion for moisture yield in the sludge. Fuel pellets were produced by rolling with technical lignosulfonate as a binding agent. Elemental analysis of the samples was conducted to study the possibility of thermal treatment using an EA 3,000 Euro Vector Analyzer.
Results. A comprehensive technology has been developed to clean the resulting gas emissions from solid particles formed during the combustion of fuel pellets and remove them from the furnace in the form of fly ash along with the outgoing gases. This technology also removed sulfur oxides, nitrogen oxides, and polychlorinated dibenzodioxins and dibenzofurans, while beneficially utilizing flue gas heat by reducing its temperature from 900–1,200°C to 140°C.
Discussion and Conclusion. The approach proposed in this article for the processing and disposal of large volumes of waste allows for the reduction of moisture content of excess activated sludge and the use of this waste as a secondary energy source. This method is environmentally friendly and addresses both technical and environmental challenges, such as the effective recycling of industrial waste and reducing the anthropogenic impact on soil, air, and groundwater. It also provides an opportunity to generate additional electrical and thermal energy through thermal utilization of waste. The results of this work indicate that it is possible to integrate the use of various types of industrial waste (sewage sludge, water treatment waste, and pulp and paper industry waste) as secondary energy sources. These findings have practical implications for enterprises in both the municipal and industrial sectors with wastewater treatment facilities.

Keywords: waste, excess activated sludge, neutralization, thermal disposal, fuel pellets, environmentally safe technology

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Научная статья

Обезвоживание и экологически безопасная термическая переработка избыточного активного ила

Р.Я. Исхакова, А.И. Нургалиев
Казанский государственный энергетический университет, г. Казань, Российская Федерация
imreginaiskh@gmail.com

Аннотация

Введение. В настоящее время существует проблема накопления многотоннажных отходов производства. Одним из таких отходов является избыточный активный ил — отход биологической очистки сточных вод, характеризующийся высокой влажностью. При депонировании избыточного активного ила на картах возникают проблемы, связанные с изменением газовоздушного фона, выделением неприятных запахов, а также загрязнением грунтовых вод и почв. Продолжительное нахождение осадка на иловых картах в бескислородных условиях приводит к его загниванию, ухудшению влагоотдающих свойств. По этой причине разработка новых подходов к утилизации многотоннажного отхода, образующегося при очистке сточных вод, является актуальной. Целью данного исследования стала разработка способа предварительного обезвреживания и термической переработки избыточного активного ила с применением отхода энергетики.

Материалы и методы. В работе использовали избыточный активный ил с влажностью 98,2 % (отход IV класса опасности). В качестве реагента для повышения влагоотдачи применяли шлам водоподготовки (отход V класса опасности). Для экспериментальных исследований по обезвоживанию использовали лабораторную центрифугу Elmi CM-6M.01, на которой проводили испытания при различных условиях (500, 1 000 и 1 500 об/сек в течение 1, 2, 3 минут) и определяли значение индекса центрифугирования как критерия влагоотдачи осадка. Топливные гранулы были разработаны методом окатывания с применением в качестве связующего технического лигносульфоната. Элементный анализ образцов с целью изучения возможности термической утилизации проводился с применением анализатора EA 3 000 Euro Vector.

Результаты исследования. Разработана комплексная технология очистки образующихся газовых выбросов от твердых частиц, образующихся при сжигании топливных гранул и выносимых из топки в виде золы-уноса с уходящими газами. При этом одновременно также удаляются оксиды серы, азота, полихлорированные дибензодиоксины и дибензофураны при условии полезного использования тепла дымовых газов за счет снижения их температуры с 900–1 200 °C до 140 °C.

Обсуждение и заключение. Предлагаемый в статье подход к переработке и утилизации многотоннажных отходов позволяет снизить влажность избыточного активного ила и использовать отход в качестве вторичного энергетического ресурса. Такой способ является экологически безопасным и позволяет решить двойную технико-экологическую задачу — эффективную переработку отходов производств, снижение антропогенной нагрузки на почвы, воздух, подземные воды, а также получение дополнительной электрической и тепловой энергии путем термической утилизации. Результаты работы свидетельствуют о возможности комплексного использования комбинации отходов различных производств (осадков сточных вод, отходов водоподготовки и целлюлозно-бумажной промышленности) в качестве вторичных энергетических ресурсов. Полученные результаты представляют практический интерес для предприятий коммунального и промышленного сектора, на которых имеются сооружения очистки сточных вод.

Ключевые слова: отходы, избыточный активный ил, обезвреживание, термическая утилизация, топливные гранулы, экологически безопасная технология

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Introduction. Ensuring environmental safety and reducing the environmental impact on the environment by developing and implementing integrated approaches to waste management is a key goal in the field of sustainable development. However, a significant amount of waste is still disposed of due to a lack of efficient waste processing and disposal facilities. The intensive growth in the volume of various categories of waste leads to an increase in the environmental burden on landfills and storage facilities every year. This results in environmental pollution problems due to improper landfill operations and the need for territorial expansion. A significant portion of the waste currently being disposed of could be recycled and reused, significantly reducing the load on landfills and providing a ready-made secondary resource for further use in the production cycle.

One of these wastes is excess activated sludge, a type of sediment formed in the process of biological wastewater treatment, which is diverted to sludge pits for drying in natural conditions. At the same time, about 100 million tons of such sediment are produced in the Russian Federation each year. The storage of excess activated sludge leads to a change in the gas-air background, the spread of unpleasant odors and bacterial contamination of soils.

Another large volume of waste product is sludge from water treatment of thermal power plants (TPP), which is generated in clarifying filters during liming and coagulation processes of natural make-up water. This sludge is discharged as a pulp into sludge reservoirs. During its storage, there is a risk of soil alkalization and increased mineralization of groundwater.

A common problem that is typical of the storage of large volumes of waste is the alienation of agricultural lands and territories, as well as an increase in anthropogenic load on the environment.

To reduce the anthropogenic load, various methods of the disposal of waste are used, including excess activated sludge [1]. For example, activated sludge is processed to obtain an adsorption material for the sorption of oil and petroleum products [2], as well as to extract phosphates and other pollutants from urban wastewater [3]. Another way to recycle activated sludge is its use as an additive to organic mineral fertilizers [4], in construction in the manufacture of concrete mix [5], as well as in the process of anaerobic fermentation to produce biogas and to use the solid phase (cake) as a fertilizer and recultivant [6]. There are works by foreign and modern authors on the use of the energy potential of excess activated sludge. For example, in [7] it is proposed to obtain hydrogen from waste activated sludge using a microbial electrolytic cell in which organic compounds can be used as a substrate. Pyrolysis of activated sludge is another way to use the energy potential and obtain additional energy during thermal decomposition of excess sludge of pre-pyrolysis gas, semi-coke and liquid fraction [8].

The aim of this work was to study and develop a method for preliminary neutralization and thermal processing of excess activated sludge using large-tonnage energy waste.

Materials and Methods. Experimental laboratory studies were conducted using excess activated sludge, which was obtained from biological wastewater treatment. The species composition of the sludge included protozoa, amoebas, rotifers, infusoria, nematodes, and actinomycetes, as well as other microorganisms.

Activated sludge had a flake-like structure that was brown in color and was a heterogeneous system with fine suspensions. Its granulometric composition was determined, with particles less than 1 mm accounting for 98% of the total, particles between 1 and 3 mm accounting for 1.5–1.8%, and particles larger than 3 mm accounting for only 0.4–0.6% of the overall composition. The density of this material was 1.11 g/cm^3. Main organic components of the sludge were proteins, fats, and carbohydrates, which made up 75–85% of its ash-free (organic) matter. The remaining 15–20% was accounted for by a lignin-humus complex [9]. Table 1 shows the component composition of excess activated sludge. Protein substances were mainly present in raw sludge, while humic compounds were present in fermented sludge [10].

Table 1

Component composition of excess sludge

Parameter	Ash content	α-cellulose	Hemicellulose	Proteins, humates	Fats	Total nitrogen	Phosphorus
%	12.00–15.00	0.80–2.00	2.20–2.60	30.00–35.00	7.11–14.00	6.80–7.30	5.40

Humidity of the activated sludge used after secondary settling tanks was 98.2%, after settling under the influence of gravity it decreased to 94%. Ash content of activated sludge was 12.2%. Excess activated sludge belonged to hazard class IV.

Chemical composition of the mineral part of the excess activated sludge included (wt. %): SiO_2 — 35.7; Al_2O_3 — 12.3; Fe_2O_3 — 7.8; CaO — 14.2; MgO — 9.4; K_2O — 0.8; Na_2O — 2.1; ZnO — 0.22; CuO — 0.12; NiO — 0.28; Cr_2O_3 — 0.23.

Excess activated sludge belongs to the group of hygrophilic organic substrates that easily rot and. For this reason, it was treated [11]. The organic part of the excess activated sludge was subject to rapid rotting with the release of an unpleasant odor, while the number of colloidal and fine particles increased, as a result of which sediment moisture yield decreased [12].

Moisture of activated sludge included free, colloid-bound and hygroscopic forms. Free moisture was not associated with solid particles and was easily removed by drying on sludge beds, filtration or extraction at low pressures, and dehydration [13]. Colloid-bound moisture was extracted from sediment with higher energy consumption, could be removed by filtration and centrifugation during coagulation. Complete removal of colloid-bound moisture was possible only by drying at elevated temperatures. Hygroscopic (or chemically bound) moisture made up to 8–10% of the total mass of water and was not removed even during thermal drying, but only by sludge combustion [14].

In addition to high humidity, activated sludge was characterized by low moisture loss, which was due to the presence of colloid-bound and hygroscopic moisture in it. Colloid-bound moisture was present in the activated sludge due to the processes of rotting of its organic part, since rotting was characterized by increased formation of fine, colloidal particles.

In the study, it was proposed to extract colloid-bound moisture by pretreating excess activated sludge with sludge from thermal power plant water treatment and further their joint centrifugation.

It was proposed to use TPP water treatment sludge as a reagent, which was a waste of hazard class V, formed during the preparation of make-up water at TPP. In this case, the slurry pulp was sent to sludge accumulators for its placement and storage. Chemical composition of carbonate sludge of Kazan TPP-1 (% by weight): Ca^{2+} — 87; Mg^{2+} — 9.7; CO_3^{2-} — 71.7; OH^- — 10.03; SO_4^{2-} — 5.7.

During the experimental studies, the moisture content of the slurry pulp was reduced from 87% to 3% by dewatering the waste in the heat drying shop. Humic substances in the amount of up to 11% of the total mass of the sample were present in the sludge, which was determined by gas chromatography-mass spectrometry [15]. The physical-chemical characteristics of the sludge were determined: bulk density — 572 kg/m^3, ash content of the sludge — 89%, moisture capacity — 56% (wt.), pH of the medium — 8.54. Granulometric analysis conducted by the sieve analysis method showed that the main fraction of the sludge (about 96%) was 0.09–0.50 mm.

During dosing, the water treatment sludge was evenly distributed among the large fibers and solid particles present in the excess activated sludge, and the sediments were thoroughly mixed.

In experimental studies, an Elmi SM-6M.01 laboratory centrifuge was used to dewater excess activated sludge. The waste pre-mixed in various proportions (activated sludge and sludge) was separated in a centrifuge at speeds of 500, 1,000 and 1,500 r/s for 1, 2, 3 minutes.

Further, the centrifugation index was determined as a criterion for sludge water yielding capacity [16].

The assessment of moisture yield and sedimentation properties of activated sludge was carried out according to the value of the centrifugation index I (cm^3/g), calculated according to formula:

$$I = \frac{V_k}{V_0 \cdot C},$$

where $V_к$ and V_0 — volume of compacted and initial sediment, cm^3; C — concentration of initial sediment, g/cm^3.

Centrifugation index, as a parameter as a criterion, allowed an assessment of the increase in the efficiency of dry matter retention during the pretreatment of excess activated sludge with water treatment sludge. After dehydration, the sediment was sent for thermal disposal. For the convenience of dosing by the rolling method, fuel pellets of 5–7 mm in size were developed. Technical powdered lignosulfonate and technical corn starch were used as a binder. Lignosulfonate was a powder from light yellow to brown in color, which was a by-product of cooking pulp. Technical corn starch was a homogeneous powdery material from white to light yellow in color and acted as one of the most multifunctional raw materials.

The choice of binders was due to their availability, low cost, low humidity (no more than 8% and 10%, respectively) and high heat of combustion (the lowest heat of combustion was 17.2 and 16.8 MJ/kg, respectively) [17]. The selected binders were explosion- and fire-proof.

Next, general technical characteristics of the obtained granules were determined: humidity, ash content, abrasion resistance, bulk density, as well as the heat of combustion of the granules. The elemental analysis of the samples was carried out using an EA 3,000 EuroVector analyzer. Based on the conducted research, a suitable scheme for gas emissions treatment was selected.

To obtain reliable data, all experimental studies were conducted at least three times.

Results. Experimental studies have shown that activated sludge was characterized by high humidity — 98.2%. For effective dewatering, centrifugation of excess activated sludge and sludge of water treatment was carried out. Figure 1 provides the results of experimental studies.

According to the results of the study, it could be seen that with an increase in the dosed sludge, the centrifugation index decreased. The most optimal choice was centrifugation of excess sludge during pretreatment with sludge in the amount of 0.6 g/dm³ for 1 minute at a speed of 1,000 r/s.

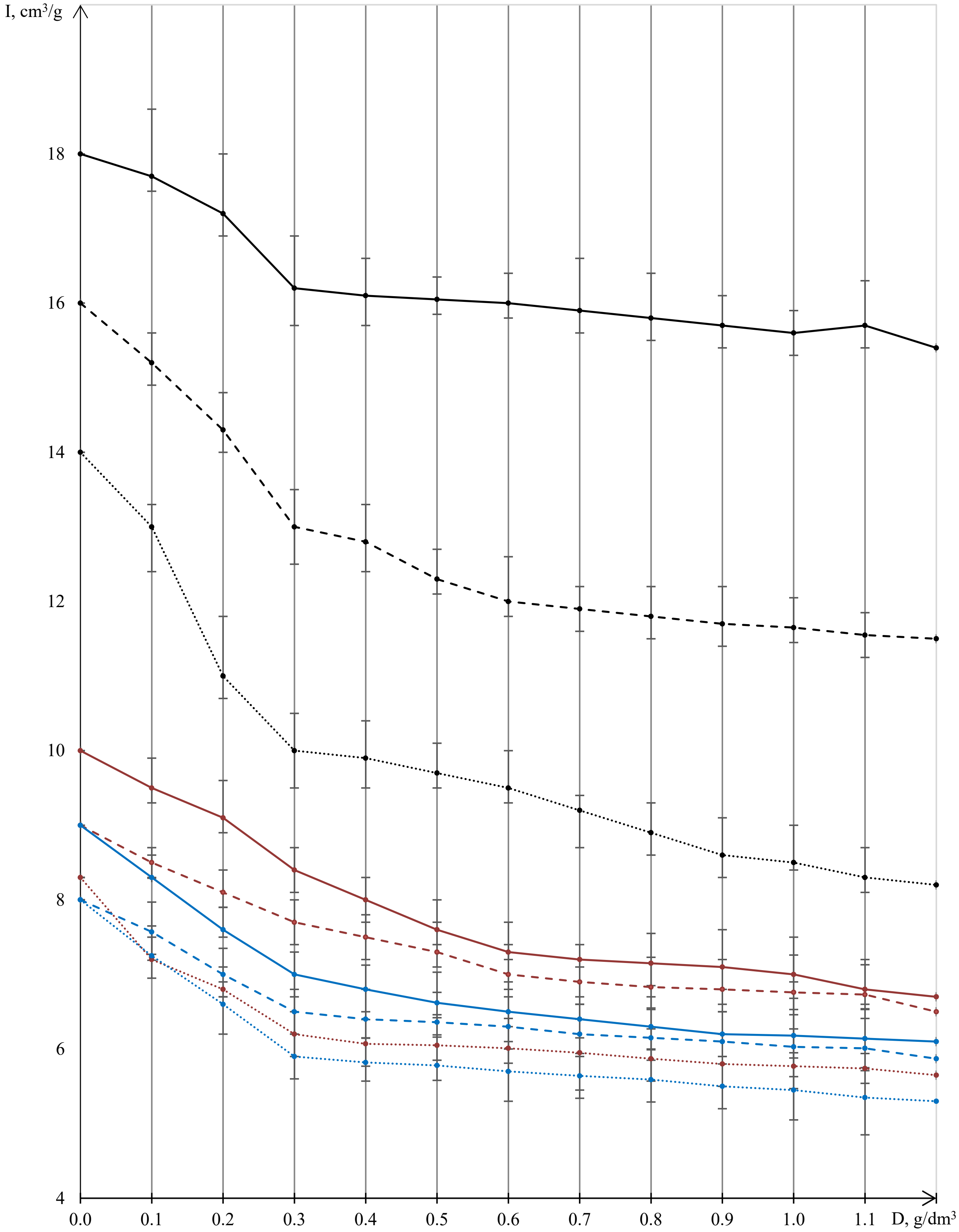

Fig. 1. Dependence of the centrifugation index value (I) on the dose of sludge (D):
— (black) — 500 rpm; — (orange) — 1 000 rpm; — (blue) — 1 500 rpm;
—— — 1 min; ▬▬ — 2 min; ▬·▬ — 3 min

During centrifugation, solid particles of water treatment sludge contributed to the rupture of colloidal systems and an increased yield of hydrate-bound moisture. The aggregative stability of excess activated sludge was disrupted, which contributed to increased moisture yield.

In addition, activated sludge particles were an amphoteric colloid and, like most microorganisms, had a negative charge at values of pH=4–9 [18]. The introduction of sludge created pH=8.54, which corresponded to the presented range of values. Activated sludge flakes were negatively charged, since the charge of polymeric substances and microorganisms was close to neutral or slightly negative. In this case, the adsorption of extracellular polymers on microorganisms occurred due to neutral groups and was not associated with a change in charge.

Positively charged Ca^{2+} cations were present on the sludge surface. The extraction of colloid-bound moisture occurred with high efficiency, since when treated with a water treatment sludge acting as a coagulant, charge neutralization and particle enlargement occurred and, as a result, there was an increase in moisture yield properties and a decrease in sediment resistivity.

As a result of pretreatment with sludge and further centrifugation, the structure of the sediment of excess activated sludge changed. Without pretreatment with sludge, the activated sludge firmly retained moisture and was characterized by low moisture yield, while colloid-bound moisture was extracted from the excess activated sludge when the sludge was introduced. As a result, a solid phase was formed, which was easily separated from the centrifuge centrate after centrifugation.

Hygroscopic or chemically bound moisture, which made up about 3–8% of the total moisture present in excess activated sludge, was extracted only during thermal utilization.

Next, the mixed sediment, having a humidity of no more than 60–64%, was sent to the molding of fuel pellets with a diameter of 5–7 mm using binders of technical lignosulfonate and technical starch. Pellets of this size were designed for convenient movement by pneumatic conveying systems, as well as to improve the accuracy of fuel dosing. As binders, preference was given to environmentally friendly substances with good heating value and bonding properties.

Important characteristics of the obtained granules, which affected the efficiency of thermal processing, were the technical and thermal properties, which are presented in Table 2.

According to the research results, the main energy indicator characterizing fuel pellets was the heat of combustion. For this reason, granules with technical lignosulfonate were selected for thermal processing, since they had higher heating value. The resulting value of the heat of combustion of the developed granules was comparable to the heating value of peat.

Table 2

Technical characteristics of fuel pellets

Samples with binders	Industrial starch (22% weight)	Industrial lignosulfonate (22% weight)
Moisture content, %	4.8±0.1	3.1±0.1
Bulk density, kg/m^3	828	788
Ash content, %	29.2	27.9
Ash color	light grey	light brown
Abrasion resistance, %	0.5	0.1
Heat of combustion, MJ/kg	9,672.6	10,345.5

Heat of combustion of fuel pellets, in addition to humidity and ash content (external fuel ballast), was determined by the ratio of the main elements (C, H, N, S) and depended on the content of combustible elements (carbon, hydrogen and sulfur) [13].

Elemental composition of fuel pellets using technical lignosulfonate showed the following values: C^p = 30.1%; H^p = 2.9%; S^p = 1.1%; N^p = 1.24%. The main combustible elements included carbon (34.1 MJ/kg) and hydrogen (120.5 MJ/kg). Sulfur and nitrogen in fuel pellets formed toxic oxides of sulfur and nitrogen, which must be extracted from gas emissions after thermal disposal. At the same time, sulfur had a lower heating value (9.3 MJ/kg), and nitrogen was present in fuel granules in the form of organic compounds and reduced the heating value of the fuel.

The technology of sediment utilization based on preliminary dewatering and their thermal processing in a circulating fluidized bed with heat recovery of waste gases formed after the process of activated sludge burning and exhaust gases cleaning was proposed (Fig. 2).

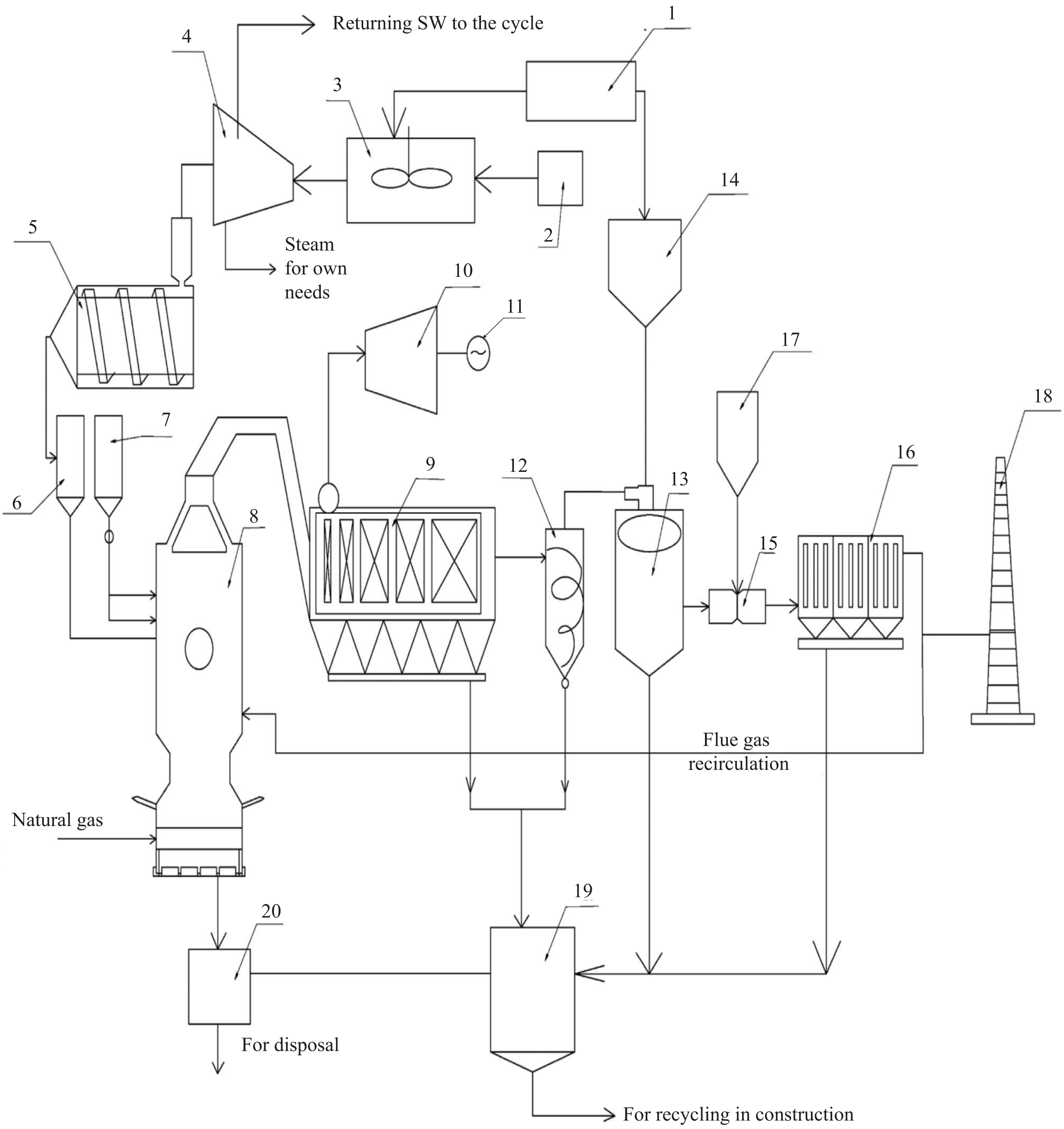

Fig. 2. Process flow diagram of thermal processing of sewage sludge:
1 — sludge storage hopper; 2 — excess activated sludge storage tank;
3 — sludge mixing hopper; 4 — decanter; 5 — granulator (extruder);
6 — fuel pellet storage hopper; 7 — inert material storage hopper; 8 — boiler with circulating fluidized bed;
9 — flue gas heat recovery boiler; 10 — steam turbine;
11 — electric generator; 12 — cyclone; 13 — spraying absorber;
14 — suspended mixture preparation hopper; 15 — activated carbon injection unit;
16 — bag filter; 17 — activated carbon storage hopper; 18 — chimney; 19 — ash and reaction products collection hopper;
20 — slag collection hopper

Combustion of granules from storage hopper 6 took place in boiler with circulating fluidized bed 8, which was characterized by the effect of fluidization or "boiling" due to an ascending gas flow and intensive mixing of particles (with the participation of an inert material from hopper 7 — sand (silicon oxide), which had a high specific heat capacity (0.835 kJ/(kg K)), stabilizing the temperature of the process with qualitative or quantitative fluctuations of fuel pellets based on activated sludge). Intense boiling of the layer contributed to the mixing of fuel granules, oxidizer, and combustion products. Therefore, there was no need for additional mechanical mixing of the granules. Natural gas was supplied for ignition during the start-up of the installation.

After combustion, gases with a temperature of about 900–1,200°C passed through heat recovery boiler 9, in which chemically desalinated water was heated to a vapor state. Steam was directed to turbine 10, and electric energy was generated using electric generator 11. Part of the steam from the heating selections was directed to the enterprise's own needs. Gases cooled to a temperature of 200-250°C were sent for purification to a filter unit consisting of mechanical cleaning and equipment for cleaning gas emissions by absorption and adsorption methods. Capture of solid dispersed particles was carried out by cyclones and bag filters. Cooled gases entered cyclones 12 to extract fly ash, as well as inert material carried out with flue gases. Next, the flue gases were sent to spraying adsorber 13, in which they were completely refined from hydrogen chloride, sulfur dioxide, nitrogen oxides, as well as partially from polychlorinated dibenzodioxins and dibenzofurans. To do this, the waste of water treatment from hopper 1 was dosed as a sorption material. After spraying adsorber 13, the temperature of the exhaust gases was 140°C. Aftertreatment from polychlorinated dibenzodioxins and dibenzofurans was carried out by spraying activated carbon from hopper 17 in unit 15 in front of the bag filters. The remaining fly ash, as well as unreacted sludge and chemical reaction products, were captured using bag filter 16 and collected in ash and reaction products collection hopper 19. After cleaning the flue gases using bag filters 16, a flue gas recirculation method was used to purify emissions into the atmosphere from nitrogen oxides by taking 20–30% of the gas media from the flue and feeding them into the active combustion zone of boiler with a circulating fluidized bed 8. After complete purification, the exhaust gases were sent to chimney 18.

Discussion and Conclusion. The research results obtained indicate the presence of an energy potential in the developed granules that can be converted into thermal and electric energy while ensuring environmental safety and minimizing negative impacts on the environment.

The choice of a circulating fluidized bed boiler is the optimal solution for this technology compared to other existing options, as the intense boiling in the bed contributes to the mixing of fuel granules, oxidizer, and combustion products, eliminating the need for additional mechanical mixing. Natural gas is used to ignite the granules during start-up.

When using fuel pellets made from activated sludge in a boiler with a fluidized bed, thermal decomposition of calcium carbonate takes place at a temperature of 900–1,200°C and then further binding of sulfur oxide to produce gypsum, followed by its removal. The following reactions occur in the bed:

$$CaCO_3 \rightarrow CaO + CO_2 + 178.8 \text{ kJ/mol};$$
$$CaO + SO_2 + 1/2O_2 \rightarrow CaSO_4 - 500 \text{ kJ/mol}.$$

Chlorine and fluorine compounds are also present in the organic part of the activated sludge. In the fluidized bed, chlorine and fluorine compounds undergo high-temperature decomposition (pyrohydrolysis) with conversion to hydrogen chloride and fluoride, which further interact with calcium oxides by the following reactions:

$$CaO + 2HCl \rightarrow CaCl_2 + H_2O;$$
$$CaO + 2HF \rightarrow CaF_2 + H_2O.$$

However, when using this solution, additional purification of gas emissions generated in a boiler with a circulating fluidized bed is required, namely: extraction of solid particles formed during combustion of fuel pellets and removed from the furnace in the form of fly ash with outgoing gases, as well as removal of residual sulfur oxides, nitrogen, polychlorinated dibenzodioxins and dibenzofurans.

The advantage of the approach proposed in the article is the possibility of neutralizing toxic combustion products that are formed during combustion.

Sulfur oxides, hydrogen chloride and fluoride, as well as polychlorinated dibenzodioxins and dibenzofurans are extracted using a spraying adsorber and adsorption aftertreatment of flue gases with activated carbon. Limestone suspension is traditionally dosed in a spray adsorber for aftertreatment. Since calcium carbonate is one of the main components of the water treatment sludge, its use as a waste reagent of thermal energy is realized. An important condition is good mixing of the suspension droplets with the exhaust gases, as well as ensuring fine spraying of the suspension.

When SO_2 is absorbed by the sludge of thermal power engineering, chemical reactions occur:

$$H_2SO_3 \leftrightarrow SO_2 + H_2O;$$
$$H_2SO_3 + CaCO_3 + H_2O \rightarrow CaSO_3 \cdot H_2O \downarrow + CO_2 \uparrow.$$

The removal of polychlorinated dibenzodioxins and dibenzofurans partially occurs in a spraying adsorber by the following reactions:

$$C_{12}H_nCl_{8-n} \cdot O_2 + (9 + 0.5n)O_2 \rightarrow (n-4)H_2O + 12CO_2 + (8-n)HCl$$

$$C_{12}H_nCl_{8-n} \cdot O + (9.5 + 0.5n)O_2 \rightarrow (n-4)H_2O + 12CO_2 + (8-n)HCl$$

This approach has shown its effectiveness in the incineration of municipal solid waste [19] and can also be implemented in practice of thermal disposal of sewage sludge.

For complete purification of flue gases from nitrogen oxides to the values of permissible emission standards, partial recirculation of flue gases is carried out by supplying them to the active combustion zone of the boiler. This approach makes it possible to reduce the concentration of NO_x to the required values. This method is widely used in the combustion processes of power boilers and can also be used for boilers with a circulating fluidized bed.

The application of the proposed method of thermal neutralization of industrial waste — excess activated sludge and sludge of thermal power engineering — by various industries allows us to preserve natural types of organic fuels and reduces the anthropogenic load on the environment. At the same time, a double technical and environmental task is solved: effective recycling of industrial waste, elimination of sludge pits, sludge collectors and related problems associated with the storage of multi-tonnage waste and alienation of territories, as well as obtaining additional energy using an environmentally safe method of thermal neutralization.

Thus, the proposed approach allows for the implementation of an environmentally friendly method of waste disposal while implementing environmental protection measures. It effectively recycles multi-tonne waste and implements the principle of energy conservation at industrial and municipal facilities that have a wastewater treatment system.

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About the Authors:

Regina Ya. Iskhakova, Cand. Sci. (Eng.), Associate Professor of the Engineering Ecology and Labor Safety Department, Kazan State Power Engineering University (51, Krasnoselskaya Str., Kazan, 420066, RF), SPIN-code: 5799-6057, ResearcherID, ScopusID, ORCID, imreginaiskh@gmail.com

Artur I. Nurgaliev, 3rd year student in the specialty Chemical Technology, Kazan State Power Engineering University (51, Krasnoselskaya Str., Kazan, 420066, RF), SPIN-code: 9360-6861, ORCID, artur_nurgaliev022@mail.ru

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RYa Iskhakova: statement of the research task, analysis of the experimental results, description of the theoretical part of the study.

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Об авторах:

Регина Яновна Исхакова, кандидат технических наук, доцент, доцент кафедры инженерной экологии и безопасности труда Казанского государственного энергетического университета (420066, РФ, г. Казань, ул. Красносельская, 51), SPIN-код: 5799-6057, ORCID, ResearcherID, ScopusID, imreginaiskh@gmail.com

Артур Ильесович Нургалиев, студент 3 курса по направлению химической технологии Казанского государственного энергетического университета (420066, РФ, г. Казань, ул. Красносельская, 51), SPIN-код: 9360-6861, ORCID, artur_nurgaliev022@mail.ru

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