Очищення та переробка відходів

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Sniezkin Yu.F., Doctor of Technical Sciences, Professor, Academician of the National Academy of Sciences of Ukraine, ORCID: 0000-0002-9049-3392,
Petrova Zh.O., Doctor of Technical Sciences, ORCID: 0000-0001-7385-8495,
Chmel V.M., Candidate of Technical Sciences, ORCID: 0000-0003-1394-7239,
Novikova Yu.P., PhD, ORCID: 0000-0002-6705-1000,
Novikova I.P., ORCID: 0000-0001-9612-286X,
Badekha A.V., ORCID: 0009-0003-3903-3766

Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine
2a, Marii Kapnist Str., 03057 Kyiv, Ukraine, e-mail: 1snezhkin@gmail.com

Processing of Old Sludge Deposits into Composite Fuel

Abstract. An urgent problem in Ukraine is overcrowded sludge sites with outdated sludge deposits. Due to the food problem, the world needs to maximize the release of land areas that have been under technical use and reclaim them for agricultural land. Therefore, the processing of obsolete sludge deposits makes it possible to reuse land for activated sludge or for reclamation for other needs of the country. The paper sets the task of studying obsolete sludge deposits to create a technology for their processing. Due to the high ash content of old silt deposits, it was proposed to combine them with peat and biomass. This will reduce ash content by 1.5–2.0 times. Since the created composite granules and the sludge deposits themselves have a high moisture of 61–68 %, the drying kinetics was studied on a convective experimental stand to reduce it. The research results showed that composite granules have a drying time of 28–39 minutes to a moisture content of 6–7 %, which is 2.3–3.1 times faster than peat. The equilibrium moisture content of composite granules was determined to be 6–7 % and not exceeding the standard moisture content for fuel granules. The heat of combustion of obsolete sludge deposits, which is 11.8 MJ/kg, and the resulting composite granules based on them, was determined, which is quite high and, depending on the composition, is in the range of 13.4–15.5 MJ/kg. During the study of the combustion of a separate fraction of aged sludge deposits, it was found that the combustion process occurs in the upward convective flow of the oxidant behind the double boundary layer. It was determined that the combustion rate is independent of its size and is the same, but the mass affects the time of ignition. Further studies
on the combustion of composite granules showed that the combustion rate of the granules is significantly lower than the combustion rate of the original biomass, but the combustion rate of a separate fraction of silt deposits prevails. Bibl. 32, Fig. 8, Tab. 1.

**Keywords:** sludge deposits, peat, biomass, drying, combustion, heat of combustion.

In Ukraine, there is an environmental problem with overcrowded landfills. For example, in Lviv, sewage treatment plants have been built according to schemes that do not provide for the use of the resulting sludge. The sludge sites of Lviv’s wastewater treatment facilities cover an area of 22 hectares, where more than 1.6 million tons of sludge have been accumulated and 3 thousand tons of fresh sludge are removed daily [1]. The Bortnytsia Aeration Station is the only wastewater treatment facility for the city of Kyiv and the adjacent villages of Kyiv Oblast, such as Irpin, Vyshneve, Hostomel, Vorzel, Bucha, Kotsiubynske, Sofiivska Borschchahivka, as well as Boryspil and Vyshhorod. It was built in the 60s for 3 million tons of sludge. The sludge pits of the Bortnytsia Aeration Station are heaps of semi-liquid mass covering 272 hectares and are a great danger because they are actually three times overcrowded-instead of the 3.5 million tons envisaged, they contain 10 million tons of sludge mass. Previously, the active sludge from this plant was used as fertilizer on the fields, but in 1986, due to the Chornobyl accident, this was banned. The current solution is to compact the sludge and burn it in special facilities, and this project should be implemented in the coming years [2, 3].

In Ukraine, in most cases, the areas where sludge deposits are stored are filled and additional areas of more than 120 hectares/year are needed. These areas can no longer cope with continuous silt flows. In Kyiv, sediments have not been removed for more than 25 years, in Smila for more than 30 years, and in Kherson for 25 years. Sludge deposits that have been stored for years need to be processed and are called “obsolete” because they have almost no organic impurities, which complicates the process of their processing. The problem of sludge utilization has not been fully resolved. While previously it was allowed to use sludge as an organic fertilizer due to its high concentration of phosphorus and nitrogen, it is also a source of pollution, as it contains extremely high levels of heavy metals and therefore cannot be used in agriculture.

The elimination of accumulated sediments is necessary for the efficient and uninterrupted operation of wastewater treatment facilities. Therefore, it is important to develop a technology for processing obsolete sludge deposits into fuel granules with simultaneous generation of heat and electricity, reclamation and return of land for agriculture. In industrialized countries, about 19–20 kg of sewage sludge solids are produced per capita per year. For example, as can be seen from Fig. 1, with a similar population in such countries as France (54.2 million people) and England (56.1 million people), the accumulation of sediments differs by 2.4 times: in France — 510 thousand tons, and in England — 1240 thousand tons. Ukraine, with a population of 42.22 million people, has a higher total amount of sediment accumulated in France

![Figure 1. Amount of sewage sludge in different countries of the world.](image-url)
and England, namely 1802 thousand tons per year. Russia is the leader in the accumulation of sewage sludge. Ukraine ranks second, but with the seventh largest annual volume of sludge [2].

Fig. 2 shows the methods of sewage sludge utilization in developed countries. All over the world, sewage sludge is disposed of through agricultural use, landfill disposal, ocean disposal, or incineration [4–7]. As shown in Fig. 2, a significant portion of sewage sludge is disposed of in landfills. Before discharging into the sea or ocean, the EU and US countries carry out biochemical treatment of activated sludge, which removes microorganisms, xenobiotics, toxic substances, heavy metals, etc.

In the sediments of the European Union, the content of heavy metals is lower than or in line with the standards [8, 9]. In post-Soviet countries, the content of most metals in sediments reaches the upper permissible limit of the standard [8]. According to the publication [8], incineration of sediments is the only way to ensure that harmful substances do not enter the environment.

The classic wastewater treatment scheme consists of primary wastewater treatment, which produces purified water and activated sludge. The resulting sludge is divided into 2 parts, one of which is added to the wastewater, and the other is anaerobically digested to produce additional biogas. After the plant is installed, it is dewatered at sludge sites. Activated sludge from the sites is supplied for use in agriculture or for incineration [2].

In the European Union, aerobic and anaerobic sewage sludge treatment is largely preferred. Most often, anaerobic treatment of sewage sludge is used in Spain, the United Kingdom, Italy, Finland, and Slovakia, and aerobic sewage sludge treatment technologies are used in the Czech Republic and Poland [10]. Studies have shown that aerobic digestion produces humic acids in large quantities in wastewater sludge, and anaerobic digestion produces proteins and aromatic amino acids, which are a component of organic-mineral fertilizers in agriculture [11].

Many countries use the incineration of sewage sludge. However, the solids content in the sludge should be 40 % and the total moisture content should not exceed 60 %. Before incineration, they must be dehydrated and dried. The sludge is incinerated in special furnaces (cyclone, drum, fluidized bed furnace). Calculations confirm that the amount of thermal energy consumed for waste incineration is 30 % higher than the energy obtained from its utilization [2, 8]. This is because their moisture is much higher than the equilibrium moisture.

When sewage sludge is incinerated, it is combined with municipal solid waste, coal, biomass and other organic impurities [1, 2]. It is also possible to gasify sludge deposits with the subsequent creation of biogas [1, 12].

One of the sludge processing technologies is the use of low-temperature pyrolysis with the addition of municipal solid waste. Waste pyrolysis occurs at a temperature of 250–400 °C. The most
low-temperature pyrolysis is implemented in Japan, Italy, Germany and other countries. The peculiarity of low-temperature pyrolysis is that the treated sludge is converted into hydrocarbons first in a gaseous state, and after condensation, the main product “crude oil” is obtained [13].

In Japan, preference is given to sludge treatment, such as incineration, gasification, drying, and carbonization [5]. At the same time, sludge deposits are a valuable source of fertilizer components, for the production of adsorbents, and for wastewater treatment from heavy metal ions [14].

According to China, the production of biogas and electricity through anaerobic digestion and dehydration is promising [15]. Simultaneous combustion of sludge and coal is used as an additional fuel in brick and cement kilns [13, 16]. In China, sludge deposits are also used to make building materials such as cement, bricks, and others [17].

Since most technologies used in the world are designed to process activated sludge with an organic content of about 80 % and 20 % mineral impurities. In Ukraine, unlike other countries, there is a problem of so-called sludge sites with “old” sludge that has been stored for years and has almost completely lost organic impurities, which significantly complicates the process of its processing. Therefore, it is advisable to combine obsolete sludge sediments with renewable resources to reduce the number of mineral impurities.

Peat occupies a special place in Ukraine, with most bogs being peatlands. The latter term is often used for drained bogs, sometimes peatland is understood as a peat deposit of a bog, especially when it is developed [18]. The geological reserves of peat amount to 2.04 billion tons, which is equivalent to 660 billion m³ of natural gas and is of industrial importance [19]. Peat fuel is the cheapest and most efficient for short-distance transportation. The cost per unit of energy obtained from peat is 3 times cheaper than the cost of the same energy obtained from natural gas [20].

In general, the economically feasible energy potential of biomass in Ukraine is about 20–25 million tons of equivalent fuel per year. Today, the greatest energy potential is in such types of biomasses as agricultural residues (primary — formed in the field during harvesting, secondary — formed at enterprises during crop processing, animal manure) and energy plants (for solid biofuels and biogas) [21].

Therefore, it is most expedient to solve the technological problem of processing “obsolete” silt deposits by developing composite fuel granules. The aim of this work is to study the combustion process of composite granules based on sludge, peat, and biomass.

Materials and methods

To create the composites, we used obsolete sludge deposits from sewage treatment plants (Fas-tiv), milled peat from the Chernihivtorg deposit, and biomass in various proportions. The biomass was added using sawdust and buckwheat husks as an example [22].

The created composites for granulation were mixed in 3 ratios: 1 — a two-component composite based on 50 % silt and 50 % peat; 2 — a three-component composite based on 45 % silt, 45 % peat and 10 % sawdust; 3 — a three-component composite based on 45 % silt, 45 % peat and 10 % buckwheat husk.

To create a marketable type of fuel for different boilers, granulation was carried out using a mechanical screw device designed to form batches of granules.

The study of drying kinetics was carried out on an experimental drying bench with automatic data collection. It allows for heat treatment with a drying agent at a temperature of 30–150 °C and a movement speed of 0.5–5 m/s [23].

To determine the calorific value, the KTS-4 calorimetric complex was used to conduct a large number of experiments to determine the calorific value of biofuel samples of different aggregate states [24]. The methodology for determining the calorific value corresponds to the standard methodology for solid fuels DSTU ISO 1928:2006 and the European standard ISO 18125:2017 “Solid biofuels — Determination of calorific value” [25, 26]. According to this standard, two or more experiments are performed to measure the heat of combustion. When processing the experimental data, the values of hydrogen and nitrogen content were used to determine the correction, as recommended in [24] and in the technical literature [25].

Ash content is the percentage of unburned residue (on anhydrous weight) that is formed from mineral impurities in fuel during its complete combustion [27]. The ash content is determined by the formula, %:

$$A = \frac{(m_3 - m_1)}{(m_2 - m_1)} \cdot 100,$$  (1)
where \( m_1 \) — weight of the crucible, g; \( m_2 \) — weight of the crucible with the sample, g; \( m_3 \) — weight of the crucible with ash, g.

Volatile substances are gaseous and vaporous products released when fossil fuels are heated. Volatile matter yield is an indicator of the quality and structural characteristics of solid fossil fuels, which is taken into account when determining their rational industrial use. It characterizes the number of thermally unstable atomic groups in solid fossil fuels [27]. The yield of volatiles is determined by the formula, %:

\[
V^\alpha = \frac{(m_2 - m_3)}{(m_2 - m_1)} \cdot 100 - W^\alpha, \quad (2)
\]

where \( m_1 \) — weight of the crucible, g; \( m_2 \) — weight of the crucible with the sample before determination, g; \( m_3 \) — weight of the crucible after determination, g; \( W^\alpha \) — analytical moisture, %.

The yield of volatiles per combustible mass of fuel (without ash and without water mass) is determined by the formula, %:

\[
V_c = \frac{(V^\alpha \cdot 100)}{(100 - (W^\alpha - A^\alpha))}, \quad (3)
\]

where \( V^\alpha \) — yield of volatiles, %; \( W^\alpha \) — analytical moisture, %; \( A^\alpha \) — analytical ash content, %.

The results of the study and their discussion

According to the research results, it was determined that the ash content of obsolete sludge piles is 47.3 % and the moisture content is 63.1 %, which is unacceptable for incineration. Peat from Chernihiv region has a rather low ash content of 14.1 %. When these materials are combined, the ash content of the composition is 33.1 %. Biomass ash content: sawdust — 3.1 %, buckwheat husk — 1.6 %.

To improve the quality and reduce the ash content of silt-peat granules, it is advisable to add sawdust and buckwheat husks. The ash content of three-component compositions is about 25 % [22]. Also, the obtained granules have a high humidity of 61–68 %, so they were dried before the combustion studies.

Study of composite fuel drying

To determine the equilibrium moisture content of the material, adsorption studies of sludge deposits, peat, biomass, and a composite based on them were conducted. To determine the equilibrium moisture content of the experimental samples depending on the relative humidity of the air \( \varphi \), the Van Bamelen strain gauge (static) method was used. The essence of the Van Bamelen method and the obtained kinetic regularities are described in previous publications [28, 29].

Fig. 3 shows the equilibrium moisture content of the components and their composites. The obtained equilibrium moisture content of the composite does not exceed the standard moisture content for fuel granules (20 %) and is 6–7 %. Therefore, further studies on the drying kinetics of composite granules were conducted up to a moisture content of 6–7 %.

The drying of a two-component composition based on old sludge deposits, peat and its components at a coolant temperature of 120 °C and a speed of 2 m/s was studied. As can be seen from Fig. 4, the peat is heated to a drying temperature of 120 °C in 30 minutes. The sludge reaches this temperature within 20 minutes, and their composite has the character of heating the sludge deposits and reaches the set temperature in 20 minutes. The drying kinetics of peat, sludge, and composite were compared.

The silt-peat composite at a coolant temperature of 120 °C to a final moisture content of 7 % dries in 39 minutes, which is 12 % more than silt and 2.3 times less than peat. The heating temperature of the material in sludge is 115 °C, peat is 119 °C, and the silt-peat composite is 117 °C.

Next, we studied the drying of two- and three-component compositions...
component pellets after pelleting in a screw mechanical device using the same coolant parameters as above. As can be seen from Fig. 5, three-component granules dry faster by 13–25 % than two-component granules based on sludge and peat. The drying time is in the range of 28–39 minutes, which is 2.2–3.1 times faster than peat.

It is advisable to carry out such drying in small volumes on an energy-efficient chamber dryer with thick-film heating elements developed at the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine [30].
Study of composite fuel combustion

The analysis of the dried pellets is presented in Table 1. As can be seen from the experimental data obtained, the heat of combustion of composite pellets is higher than the standard values of the components. Specific heat of combustion of peat is 12.1 MJ/kg; obsolete sludge deposits 11.8 MJ/kg; buckwheat husk 18.2 MJ/kg; sawdust 16.4 MJ/kg. The heat of combustion of two-component granules is 10 % higher than that of sludge and 12 % higher than that of peat. For three-component granules, the value is 20–24 % higher than sludge and 17–20 % higher than peat, but lower than buckwheat husk by 18–19 % and sawdust by 17–20 %.

The energy performance of sludge-based granules is quite high (Table 1), which allows them to be used as an alternative fuel for industrial needs. As we can see, the pellets have high fuel characteristics with a combustible mass of 60–70 %. The high content of volatiles ensures that the resulting granules are highly flammable.

Initially, a study was conducted on the incineration of a separate part of the outdated sludge deposits. In addition, the effect of heat removal on the combustion process was studied. The ignition of a separate fraction of sludge deposits was carried out by intensive heating with an external heat source. It takes 1.85 seconds to completely ignite a fraction of low-mass sludge due to the combustion of volatile sediments. But with an increase in mass, the ignition time increases.

It was also found that the combustion process occurs in the upward convective flow of the oxidizer behind the double boundary layer. Around the sludge deposits particle, there is a high-temperature zone in which the combustion of the gas phase occurs — the flame front (shown by the dotted line). It occurs when a particle ignites due to the combustion of volatiles that move from fuel particles to the flame front, to which the oxidizing agent, air oxygen, moves from the outside. The flame front is established in the zone of the stoichiometric ratio of the oxidizer and fuel, and the temperature in the combustion reaction zone is determined by the heat of combustion of the fuel. This is how the normal combustion process — deflagration — takes place. Combustion products diffuse from the flame front in both directions, the main component of which is carbon dioxide CO₂. The combustion process at the flame front occurs between the gas phases: oxidizer and fuel and is homogeneous. After the sludge particle is heated, the carbon dioxide that diffuses towards the fuel particle interacts with carbon on its surface, resulting in carbon gasification and the creation of carbon monoxide CO, which diffuses to the flame front and burns out instead of the yield of volatiles.

The temperature of the combustion products of individual sludge deposit particles is in the range of 690–750 ºC. Given that the combustion process of sludge deposits occurs behind a double boundary layer, the decay of particle combustion occurs with a decrease in the speed of the heterogeneous process. The latter occurs due to heat loss to the environment and a decrease in the heat supply from the flame front — a homogeneous process. At the same time, the gasification reaction on the particle surface slows down and gradually dies down, which leads to a decrease in flame size and its attenuation.

Experiments on the combustion of a single

<table>
<thead>
<tr>
<th>Component</th>
<th>Lower heat of combustion, MJ/kg</th>
<th>Ash content A, %</th>
<th>Combustible weight, %</th>
<th>Yield of volatiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-component granules in the proportion of 50% sludge/50% peat</td>
<td>13.4</td>
<td>32.4</td>
<td>61.6</td>
<td>40.5</td>
</tr>
<tr>
<td>Three-component granules in the proportion of 45% sludge/45% peat/10% buckwheat husk</td>
<td>14.6</td>
<td>24.9</td>
<td>70.8</td>
<td>51.7</td>
</tr>
<tr>
<td>Three-component granules in the proportion of 45% sludge/45% peat/10% sawdust</td>
<td>15.2</td>
<td>23.1</td>
<td>72.6</td>
<td>46.2</td>
</tr>
</tbody>
</table>
particle of sludge deposits have shown that as a result of sludge combustion behind a double boundary layer, the combustion rate per unit surface of the particle is independent of its size and is the same. This is evident from the graph (Fig. 6), where particles of different mass burn at the same rate. The burning rate \( u, \text{ kg/hour} \) of a sludge particle is about \( 6 \text{ kg/hour} \).

The combustion of composite granular fuel was studied in an experimental setup that allows burning fuel in a high-speed (compressed) bed at different pressure drops on it. In this case, combustion at low pressure drops makes it possible to simulate fuel combustion in a conventional layer [31]. The combustion of composite fuel was studied at rarefactions of 100, 250, and 500 Pa. Fig. 7 shows the combustion flame of two-component pellets based on silt and peat with a rarefaction pressure of 250 Pa, it has a high-temperature core at the initial section and a sufficiently long tail, in which the particles of fuel carryover burn out.

The combustion rate in the high-speed (compressed) layer (Fig. 8) of composite fuel granules was determined: a two-component composition based on sludge and peat; a three-component composition based on sludge, peat, and sawdust; a three-component composition based on sludge, peat, and buckwheat husk. The combustion rate in a straight-flow bed depends on both the pressure drop across the bed (the velocity gradient in the bed) and the type of fuel. The combustion rate is also affected by the content of volatile compounds.

As can be seen, the fuel characteristics of the granules differ significantly from the fuel characteristics of the feedstock. The combustion rate of granules: a two-component composition based on sludge and peat — 1, a three-component composition based on sludge, peat and sawdust — 2, a three-component composition based on sludge, peat and buckwheat husk — 3, is significantly lower than the combustion rate of the initial biomass: wood — 4, and peat — 5 [32]. This is explained by a decrease in the reaction surface and
Conclusion

The determined technical properties of obsolete sludge deposits revealed a large amount of ash, which requires its reduction for further combustion and utilization. Therefore, the optimal ratio of composite components was selected, which improves quality and reduces ash content.

Due to the high moisture content of the pellets, a drying study was performed, the results of which showed that the process duration is within 28–39 minutes and 2.3–3.1 times faster than peat.

Adsorption studies have been conducted to determine the equilibrium moisture and optimal storage conditions for composite granules, which allow not to lose the quality characteristics of these granules as fuel.

The determined heat of combustion of sludge-based granules is high enough that they can be used as an alternative fuel.

The combustion process of composite granules was studied, which showed that the results obtained can be used in the combustion of fuel in different ways or in the creation of new methods of combustion.

The obtained results make it possible to develop a technology for processing obsolete sludge deposits into composite fuel based on them.

References


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Снєжкін Ю.Ф., докт. техн. наук, проф., акад. НАН України,  
ORCID: 0000-0002-9049-3392,  
Петрова Ж.О., докт. техн. наук,  
ORCID: 0000-0001-7385-8495,  
Чмель В.М., канд. техн. наук,  
ORCID: 0000-0003-1394-7239,  
Новікова Ю.П., докт. філософ. наук,  
ORCID: 0000-0001-9612-286X,  
Бадеха А.В., 0009-0003-3903-3766

Інститут технічної теплофізики Національної академії наук України  
вул. Марії Каніс, 2а, 03057 Київ, Україна, e-mail: 1snezhkin@gmail.com

Переробка застарілих мулових відкладень  
на композитне паливо

Анотація. Актуальною проблемою в Україні є переповнені мулові майданчики із застарілими муловими відкладеннями. У зв’язку з продовольчою проблемою у світі потрібно максимально вивільнити земельні площі, який було під технічним використанням, та здійснювати їх рекультивацію для сільськогосподарських угод. Переробка застарілих мулових відкладень дає можливість для повторного використання земель під активний мул або для рекультивації під інші потреби країни. У статті досліджено застарілі мулові відкладення для створення технології їх переробки. У зв’язку з підвищеною зольностю застарілих мулових відкладень було запропоновано комбіновану їх з торфом, біомасою, що дає можливість зменшувати зольність у 1,5–2,0 рази. Оскільки створені композитні гранули та самі мулові відкладення мають високу вологість 61–68 %, для її зменшення виконано дослідження кінетики сушіння на конвективному експериментальному стенді. Результати дослідження показали, що композитні гранули мають тривалість сушіння в межах 28–39 хв до вологості 6–7 %, що у 2,3–3,1 рази швидше за торф. Визначено рівноважну вологість композитних гранул, яка дорівнює 6–7 % та не перевищує стандартну вологість для паливних гранул. Визначено також теплоту згоряння застарілих мулових відкладень, яка становить 11,8 МДж/кг, та одержаних композитних гранул на їх основі, яка достатньо висока та знаходиться в межах 13,4–15,5 МДж/кг у залежності від складу. При дослідженнях спалювання окремої частки застарілих мулових відкладень з’ясовано, що процес горіння відбувається у вихідному конвективному потоці окислювача за подвійним погранічним шаром. Визначено, що швидкість горіння цих відкладень незалежна від їх розміру та однакова, але при цьому маса впливає на час займання. Дослідження спалювання композитних гранул показали, що швидкість горіння гранул значно нижча за швидкість горіння вихідної біомаси, однак переважає швидкість горіння окремої частки мулових відкладень. Бібл. 32, рис. 8, табл. 1.

Ключові слова: мулові відкладення, торф, біомаса, сушіння, спалювання, теплота згоряння.

Список літератури
1. Клюс В.П., Четверик Г.О., Маслюкова З.В. Технології переробки осадів стічних вод каналізаційних очисних споруд. Відновлювана енергетика. 2018. № 1. С. 78–84.
7. Zhen G., Lu X., Kato H., Zhao Y., Li Y.-Y. Over-


32. Чмель В.М., Новікова І.І. Брикетування біомаси. Відновлювана енергетика. 2007. № 4. С. 98–103.