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KINETICS OF THE DRYING PROCESS OF COMPOSITE BIOPELLETS ON A CONVECTIVE DRYING BENCH

Zhanna O. Petrova
bergelzhanna@ukr.net
ORCID: 0000-0001-7385-8495

Vadym M. Paziuk
vadim_pazuk@ukr.net
ORCID: 0000-0002-4955-1941

Yuliia P. Novikova
yuliianovikova3@gmail.com
ORCID: 0000-0002-6705-1000

Anton I. Petrov
monoton10@gmail.com
ORCID: 0000-0003-4851-3115

Institute of Technical Thermophysics of NAS of Ukraine
2a, Maria Kapnist str., Kyiv, 03057, Ukraine

In Ukraine, there is a problem of overflowing sediment maps, to which activated sludge, which eventually turns into sludge deposits, is constantly added. The accumulated sludge deposits are outdated, have lost most of their nutrients, became too mineralized and are practically unsuitable for direct biofuel production. The elimination of accumulated sediments is necessary for the efficient and uninterrupted operation of treatment plants, as well as for land reclamation. However, due to the energy crisis around the world, it is possible to use them with the creation of fuels based on obsolete sludge, peat and biomass to solve this problem. Therefore, it is important to develop a technology for processing obsolete sludge into fuel pellets that can be used as fuel for, as an example, mini-CHPPs that simultaneously produce heat and electricity. Since obsolete sludge deposits have a low content of organic matter, it is proposed to create composite pellets for their better utilization, followed by their drying and combustion, in which the resulting ash will be used to make building materials. Therefore, the aim of the study was to investigate the drying processes of composite pellets on a convective plant and generalize them with a theoretical calculation. The drying processes of composite pellets based on obsolete sludge deposits, peat and biomass and identifies effective drying modes are studied in the paper. As a result, the influence of the coolant temperature on the drying time of the sludge-peat composition was determined, which shows that an increase in temperature reduces the drying time of the pellets by 1.4 times. Comparison of the drying kinetics of two- and three-component pellets at 80 °C and 120 °C indicates that the drying time of three-component pellets is by 1.1 to 1.4 times shorter than that of two-component pellets. Increasing the temperature of the coolant reduces the drying time of three-component pellets by about 1.5 times. Theoretical studies with the construction of generalized drying curves for composite pellets calculated by the method of V. V. Krasnikov showed a coincidence with experimental data. The relative and kinetic drying coefficients were calculated from the generalized drying curves and the drying speed, and the formulas for the drying time of two- and three-component pellets were obtained.

Keywords*: sludge deposits, peat, biomass, granulation, briquettes, drying.*

Introduction

For Ukraine, the current problem is the overflow of sediment maps, as the activated sludge, which eventually turns into sludge deposits, is constantly added. Sediment maps (sludge deposits), or sludge sites, are land plots with sealed bottoms, which are specially fenced off with waterproof materials, designed for dewatering sludge deposits by drainage or naturally. The deposits are then collected, and the plots can be reused. However, failure to comply with technology often leads to environmental pollution. For example, overflowing sediment maps negatively affect the environmental situation in Ukraine, contaminating groundwater and soils with toxic substances. It is also worth mentioning that the disadvantages of sediment maps are their narrow capabilities, which is explained by the need to stop operation at ambient temperatures below the freezing point of water. So, in winter, the processes of sludge deposits processing become more complicated [1].

In addition, problems arise when processing "old" (obsolete) sludge deposits, which include those that are over 30 years old. This is explained by the fact that they have almost no organic component [2].

A literature review of wastewater sludge processing technologies in Ukraine and around the world is given in paper [2]. One of the new technologies is sludge utilization by using vermiculture, which disinfects and increases the efficiency of sludge treatment, reducing discharge to sediment maps. The technology consists in processing sludge using worms, which makes disposal cheaper compared to irrigation in the fields.

Many countries incinerate activated sludge with solid municipal waste. The technology consists in drying a composition based on solid municipal waste and sludge deposits, which are burned in special furnaces. However, when using this technology, another problem arises. The problem is the high energy costs for drying activated sludge with high humidity. Currently, the technology of sludge treatment in biogas plants is recognized as an effective method of sludge decontamination and processing, which consists in mixing heated raw sludge with fermented sludge in a ratio of 1:10. This produces biogas and ecological fertilizers [2].

In paper [3], a study on the creation of cement from activated sludge is given. Cement production was carried out from ash after incineration of activated sludge, as a replacement for slag cement, which is very profitable from an economic point of view. The use of sewage slag ash will allow to obtain the aforementioned commercial benefit and environmental support, which is provided by two plants.

When processing activated sludge, its anaerobic decomposition is popular for creating biogas [4–9] as a mature technology that makes the efficient and economical utilization of biomass waste possible. It has attracted widespread interest because it generates biogas (CH_4 and CO_2, as well as microgases including hydrogen sulfide, hydrogen and nitrogen, among others) by processing organic waste, which reduces environmental pollution [4, 10, 11].

In recent years, trends in environmental management have evolved from waste disposal to recycling and disposal in the context of a circular economy [12, 13]. Many waste disposal processes aim at complete oxidation of the sludge, i.e. the production of mainly biofuels [14, 15]. However, this approach leads to the loss of value-added products present in the sludge, since it is mainly composed of bacteria and other microorganisms [12]. For this reason, waste from waste is considered an excellent source of biorefinery products [16–19]. The creation of such bioproducts requires the controlled destruction of biological structures. Less aggressive solubilization processes allow the release of enzymes [20–23], bioplastics [24, 25], proteins [26, 27], humic acids [27, 28] and lipids [29–31] into liquid media. The use of water-accumulative treatment by recovering biocompounds such as proteins, enzymes, humic acids, lipids or short-chain fatty acids seems interesting from an economic point of view.

However, most of the technologies around the world and those given in the paper are used for processing activated sludge.

Aim of the paper is a study of the drying process of composite pellets on a convective plant and generalization by theoretical calculation.

To achieve the set goal, the following tasks were solved: study of the drying process of composite raw materials based on peat, obsolete sludge deposits and biomass; generalization of experimental data with theoretical calculation, calculation of relative and kinetic coefficients of drying, obtaining formulas for the duration of two- and three-component pellets drying.

Materials and methods

Two- and three-component compositions for granulation were prepared from obsolete sludge deposits, milled peat and biomass [32] and subjected to granulation using a screw-type mechanical device. After they were formed on a convective drying plant, which allows for heat treatment with a drying agent at a temperature of 30–50 °C and a speed of 0.5–5 m/s [33], the kinetics of pellets drying was studied.

Research results

The temperature curves and kinetics of the sludge-peat pellets drying (in the proportion of 50% sludge / 50% peat) on a convective drying plant at temperatures of 80 ºC and 120 ºC is shown in Fig. 1.

The drying time of sludge-peat pellets with an increase in the temperature of the coolant from 80 to 120 ºC decreases by 29.5% (Fig. 1). At a moisture content of the pellets of 10%, the temperature in them is 72 ºC. Their heating at a temperature of the coolant of 80 ºC occurs evenly. At a temperature of 120 ºC, the pellets heating occurs more intensively and at the corresponding humidity, the temperature in them is 115 ºC.

The drying speed of peat pellets with an increase in temperature from 80 to 120 ºC increases from 3.8 to 5.5 %/min. (Fig. 2).

The drying of three-component pellets after granulation in a screw press with the inclusion of 10% sawdust or 10% buckwheat husks in the sludge-peat mixture was also studied.

Three-component pellets dry by 13–25% faster compared to two-component ones based on sludge and peat (Fig. 3).

Similarly, we dry two- and three-component pellets at a coolant temperature of 80 ºC (Fig. 4).

It was found that drying three-component mixtures at a coolant temperature of 80 ºC accelerates the process by 10–16%. In three-component pellets in the proportion of 45% sludge / 45% peat / 10% buckwheat husk, the highest heating temperature is observed – it is equal to 78.7 ºC. For three-component pellets in the proportion of 45% sludge / 45% peat / 10% sawdust, the lowest heating temperature is recorded – it is 70.3 ºC.

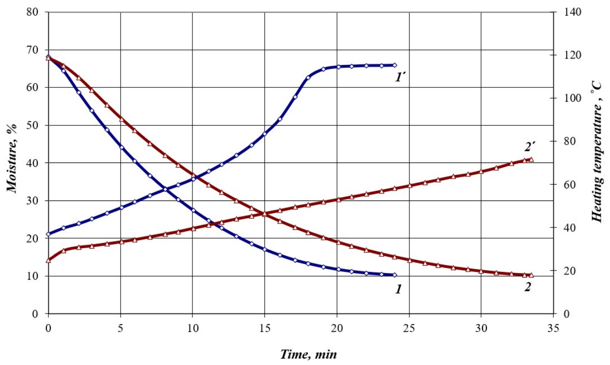

Fig. 1. Change in temperature inside the pellet 1', 2') and humidity (1, 2) of sludge-peat pellets in the proportion of 50% sludge / 50% peat at a coolant speed of 2 m/s, pellet diameter of 6 mm:
1, 1' – 120 ºC; 2, 2' – 80 ºC

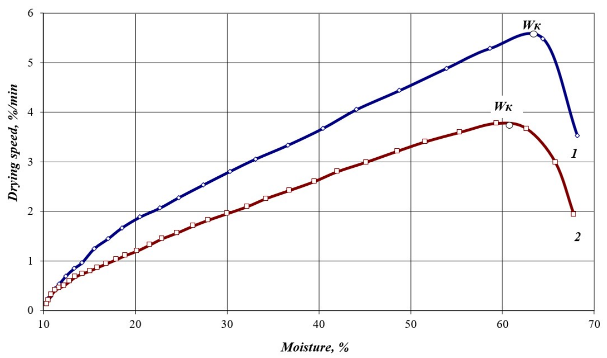

Fig. 2. Change in the drying speed of sludge-peat pellets in the proportion of 50% sludge / 50% peat at a coolant speed of 2 m/s, a pellet diameter of 6 mm:
1 –120 ºC; 2 – 80 ºC

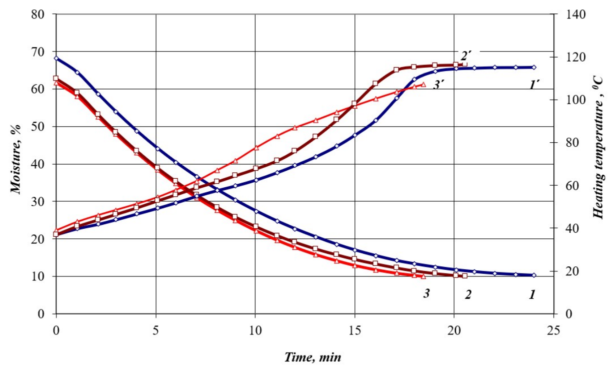

Fig. 3. Change in temperature inside the pellet (1', 2', 3') and humidity (1, 2, 3) of two- and three-component pellets at a coolant temperature of 120 ºC, coolant speed of 2 m/s, and a pellet diameter of 6 mm:
1, 1' – two-component pellets in the proportion of 50% sludge / 50% peat;
2, 2' – three-component pellets in the proportion of 45% sludge / 45% peat / 10% buckwheat husk;
3, 3' – three-component pellets in the proportion of 45% sludge / 45% peat / 10% sawdust

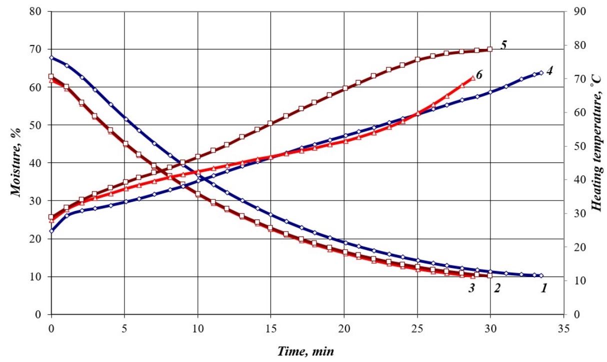

Fig. 4. Change in temperature inside the pellet (1', 2', 3') and humidity (1, 2, 3) of two- and three-component pellets at a coolant temperature of 80 ºC, coolant speed of 2 m/s, and a pellet diameter of 6 mm:
1, 1' – two-component pellets in the proportion of 50% sludge / 50% peat;
2, 2' – three-component pellets in the proportion of 45% sludge / 45% peat / 10% buckwheat husk;
3, 3' – three-component pellets in the proportion of 45% sludge / 45% peat / 10% sawdust

Based on the conducted research, it was determined that the addition of sawdust or buckwheat husks as an organic component reduces the drying time (Fig. 4) and increases the drying speed (Fig. 5).

The dependence of the drying speed on the humidity of two- and three-component pellets is shown in Fig. 5. Thus, in two-component sludge-peat pellets, the drying speed at the critical point $W_к$ is lower than that of three-component pellets and is 3.8%/min. In turn, in three-component pellets at the critical point $W_к$ the drying speed is 4 %/min, which is 0.2% higher. At a pellet moisture content of 42%, the drying speeds of two- and three-component pellets coincide.

It has been established that the nature of the drying process, as indicated by drying kinetics curves, drying speed, and temperature curves, is determined by the physicochemical and structural-mechanical properties of the material, which influence the form of moisture binding,the diffusion-based nature of the phenomenon, and the method of heat supply – governed by the regularities of interaction between the body and the surrounding environment. The variety of factors and their interrelationships complicates the obtaining of analytical dependences of the drying kinetics of the material. Therefore, empirical dependences are used when describing the drying process. The most similar method for calculating the drying kinetics is the method based on the study of general regularities of the process, which approximates the theory and practice of drying [34, 35].

The drying process is described by drying curves, which characterize the change in the average (integral) moisture content of the material W during drying τ [36], and by drying speed curves, which are constructed by the method of graphical differentiation from drying curves [36].

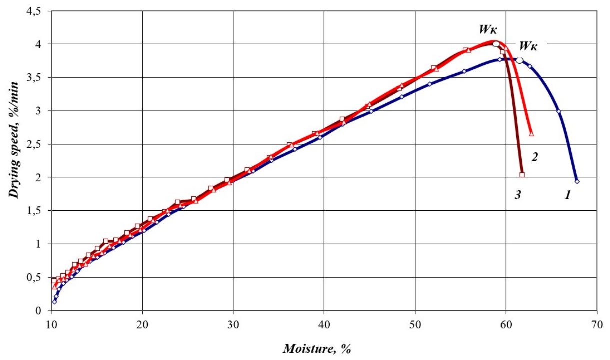

Fig. 5. Change in the drying speed of two- and three-component pellets at a coolant temperature of 80 ºC, coolant speed of 2 m/s, and a pellet diameter of 6 mm:
1 – two-component pellets in the proportion of 50% sludge / 50% peat;
2 – three-component pellets in the proportion of 45% sludge / 45% peat / 10% buckwheat husk;
3 – three-component pellets in the proportion of 45% sludge / 45% peat/10% sawdust

The drying curves have two main sections separated by a vertical line: the first period is the period of constant speed; the second one is the period of decreasing speed. These sections are separated by the critical moisture content (W_k), which is determined by the break point of the straight line (of the first period) [37].

To compare the experimental results and theoretical calculations, heat and moisture exchange was performed. To calculate the kinetics of heat and moisture exchange during the drying of composite pellets, the method of V. V. Krasnikov was used [34, 35].

To study the kinetics of drying, composite pellets based on sludge and peat were taken in the proportion of 50% sludge / 50% peat, pellets with the addition of 10% sawdust were taken in the proportion of 45% sludge / 45% peat / 10% sawdust, and with the addition of 10% buckwheat husks – in the proportion of 45% sludge / 45% peat/10% buckwheat husks.

To determine the relative drying coefficients of the created composite pellets, we construct generalized drying curves in the semi-logarithmic coordinate system *lg W* depending on the experiment time τ (Fig. 6).

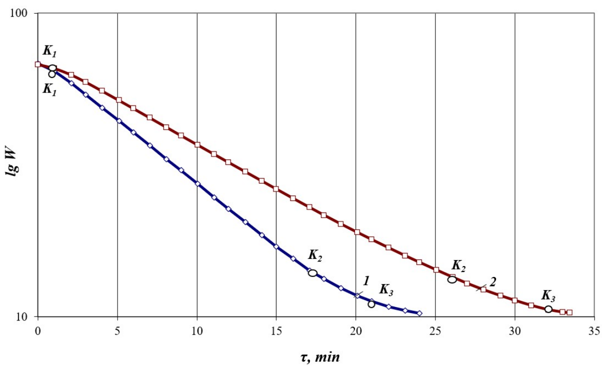

Fig. 6. The influence of the coolant temperature on the drying time of sludge-peat pellets in the proportion of 50% sludge / 50% peat in a semi-logarithmic coordinate system at a coolant speed of 2 m/s:
1 – 120 ºC; 2 – 80 ºC

The given drying curves of sludge-peat pellets in semi-logarithmic coordinates in Fig. 6 indicate that the second period consists of three parts with critical points K_1, K_2 and K_3. As can be seen in the figure, the lower the temperature of the coolant, the later the critical points occur and the process goes more slowly.

Similarly, we construct generalized drying curves in the semi-logarithmic coordinate system *lg W* depending on the experiment time τ for three-component pellets (Fig. 7–8).

The given drying curves of composite three-component pellets in semi-logarithmic coordinates in Fig. 7 and 8 indicate that the second period consists of two parts with critical points K_1 and K_2. In addition, it was found that the lower the temperature of the coolant, the later the critical points occur and the slower the process goes.

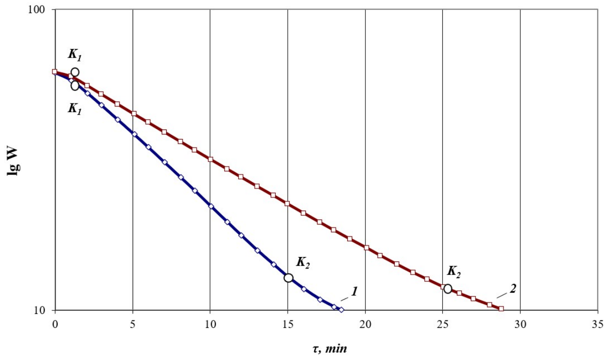

Fig. 7. The effect of the coolant temperature on the drying time of a three-component pellet in the proportion of 45% sludge / 45% peat / 10% sawdust in a semi-logarithmic coordinate system at a coolant speed of 2 m/s:
1 – 120 ºC; 2 – 80 ºC

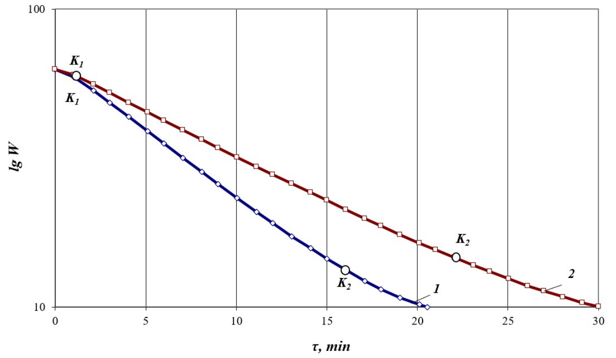

Fig. 8. The influence of the coolant temperature on the drying time of a three-component pellet in the proportion of 45% sludge / 45% peat / 10% buckwheat husk in a semi-logarithmic coordinate system at a coolant speed of 2 m/s:
1 – 120 ºC; 2 – 80 ºC

When mathematically describing the kinetics of moisture exchange during drying in the second period, the values, or rather, empirical coefficients, determined by the properties of the given material should be taken into account. These coefficients should be determined directly from the experiment. The relative drying coefficient χ is calculated only by the formula for the relation between moisture and the material, its structure, and density, and does not depend on the processing mode.

The values of the relative drying coefficients of composite pellets in the second period are determined from Fig. 6 using mode 1 as an example. They are equal to [6]

$$\chi_1 = \frac{\lg W\kappa_1 - \lg W\kappa_2}{N\tau_1} = \frac{\lg 64.4 - \lg 14.2}{5.48 \cdot 16} \approx 0.008\,;$$

$$\chi_2 = \frac{\lg W\kappa_2 - \lg W\kappa_3}{N\tau_2} = \frac{\lg 14.2 - \lg 11.24}{5.48 \cdot 4} \approx 0.005\,;$$

$$\chi_3 = \frac{\lg W\kappa_3 - \lg W\kappa}{N\tau_3} = \frac{\lg 11.24 - \lg 10.26}{5.48 \cdot 2} \approx 0.004\,.$$

Let’s calculate the kinetic coefficients of drying in the second period of composite pellets for mode 1 in Fig. 6 using mode 1 as an example [6]

$$K_1 = \chi_1 \cdot N = 0.008 \cdot 5.48 \approx 0.044 \text{ min}^{-1};$$

$$K_2 = \chi_2 \cdot N = 0.005 \cdot 5.48 \approx 0.027 \text{ min}^{-1};$$

$$K_3 = \chi_3 \cdot N = 0.004 \cdot 5.48 \approx 0.022 \text{ min}^{-1}.$$

All calculations of drying coefficients are summarized in Tables 1, 2.

Depending on the range between the critical points, the relative and kinetic drying coefficients change. In mode 1, which corresponds to a coolant temperature of 120 ºC, the relative coefficients are higher than in mode 2 at a coolant temperature of 80 ºC (Table 1, 2).

Table 1. Relative and kinetic drying coefficients of two-component pellets (sludge-peat)

No.	Pellet name	Critical humidity range, %	Relative drying coefficients			Drying kinetic coefficients		
			χ_1	χ_2	χ_3	K_1	K_2	K_3
1	Sludge-peat pellets 50% sludge / 50% peat Mode 1 (t=120 ºC, V=1.5 m/s)	64.4 – 14.2	0.008			0.044		
		14.2 – 11.2		0.005			0.027	
		11.2 – 10.2			0.004			0.022
2	Sludge-peat pellets 50% sludge / 50% peat Mode 2 (t=80 ºC, V=1.5 m/s)	65.8 – 13.5	0.007			0.026		
		13.5 – 10.54		0.005			0.019	
		10.54 – 10.29			0.013			0.049

Table 2. Relative and kinetic drying coefficients of three-component pellets (sludge-peat + sawdust or sludge-peat + buckwheat husk)

No.	Pellet name	Critical humidity range, %	Relative drying coefficients		Drying kinetic coefficients	
			χ_1	χ_2	K_1	K_2
1	Sludge-peat pellets + buckwheat husk 45% sludge / 45% peat / 10% buckwheat husk Mode 1 (t=120 ºC, V=1.5 m/s)	58.9 – 13.3	0.010		0.043	
		13.3 – 10.2		0.005		0.028
2	Sludge-peat pellets + buckwheat husk 45% sludge / 45% peat / 10% buckwheat husk Mode 2 (t=80 ºC, V=1.5 m/s)	60.0 – 14.6	0.007		0.029	
		14.6 – 10.0		0.005		0.021
3	Sludge-peat pellets + sawdust 45% sludge / 45% peat / 10% sawdust Mode 1 (t=120 ºC, V=1.5 m/s)	58.1 – 11.8	0.009		0.047	
		11.8 – 10.0		0.044		0.240
4	Sludge-peat pellets + sawdust 45% sludge / 45% peat / 10% sawdust Mode 2 (t=80 ºC, V=1.5 m/s)	59.7 – 14.2	0.008		0.031	
		14.2 – 10.1		0.005		0.020

The generalized drying speed curves in the humidity coordinate system W with a generalized change or generalized drying time $N_{max}\cdot\tau$ is given in Fig. 9. Analyzing the generalized drying curves, we can say that all modes fit on one curve with an error of no more than 10% (Fig. 9). According to the $N_{max}\cdot\tau$ complex, the fastest process occurs when drying three-component pellets in the proportion of 45% sludge / 45% peat / 10% sawdust.

By performing graphical differentiation of the generalized drying kinetics curve given in Fig. 9, we obtained the generalized drying speed curve of composite pellets shown in Fig. 10.

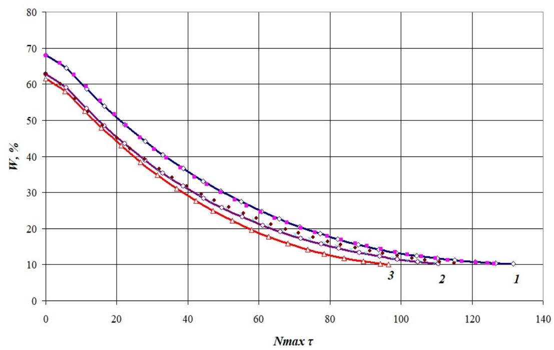

Fig. 9. Generalized drying curves of composite pellets in the coordinate system W – $N_{max}\cdot\tau$:
1 – sludge-peat pellets in the proportion of 50% sludge / 50% peat;
2 – three-component pellets in the proportion of 45% sludge / 45% peat / 10% buckwheat husk;
3 – three-component pellets in the proportion of 45% sludge / 45% peat / 10% sawdust

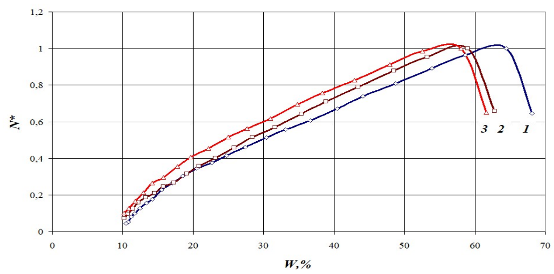

Fig. 10. Generalized drying speed curves (N^*) of composite pellets:
1 – sludge-peat pellets in the proportion of 50% sludge / 50% peat;
2 – three-component pellets in the proportion of 45% sludge / 45% peat / 10% buckwheat husk;
3 – three-component pellets in the proportion of 45% sludge / 45% peat / 10% sawdust

The total duration of the drying process τ_T (excluding the warm-up period) consists of the duration of drying in the first period τ_I, τ_1 in the 1st, τ_2 in the 2nd and τ_3 in the 3rd parts of the second period

$$\tau_T = \tau_I + \tau_1 + \tau_2 + \tau_3 . \qquad (1)$$

Given that the first drying period is not observed when drying pellets, formula (1) takes the form

$$\tau_T = \tau_1 + \tau_2 + \tau_3 .$$

Drying duration in the 1st part of the second period

$$\tau_1 = \frac{1}{\chi_1 N} \lg \frac{W\kappa_1}{W\kappa_2} .$$

Drying duration in the 2nd part of the second period

$$\tau_2 = \frac{1}{\chi_2 N} \lg \frac{W\kappa_2}{W\kappa_3}.$$

Drying duration in the 3rd part of the second period

$$\tau_3 = \frac{1}{\chi_3 N} \lg \frac{W\kappa_3}{W\kappa}.$$

Total process duration

$$\tau_T = \frac{1}{N}\left(\frac{1}{\chi_1} \lg \frac{W\kappa_1}{W\kappa_2} + \frac{1}{\chi_2} \lg \frac{W\kappa_2}{W\kappa_3} + \frac{1}{\chi_3} \lg \frac{W\kappa_3}{W\kappa}\right)$$

The total duration of the pellets drying is calculated and summarized in Table 3 [4].

Table 3. Duration of the drying process of composite pellets

No.	Name of composite pellets	Estimated duration of the drying process, min
1	Sludge-peat (50% sludge / 50% peat)	$\tau_T = \frac{112.47}{N}$
2	Sludge-peat with the addition of buckwheat husks (45% sludge / 45% peat / 10% buckwheat husks)	$\tau_T = \frac{86.0}{N}$
3	Sludge-peat with the addition of sawdust (45% sludge / 45% peat / 10% sawdust)	$\tau_T = \frac{78.4}{N}$

Conclusions

1. The drying processes of composite pellets based on obsolete sludge deposits, peat and biomass were investigated, and effective drying modes were established.

2. The kinetic regularities of convective drying of two- and three-component pellet compositions have been determined and generalized.

3. From the generalized drying curves and drying speed, relative and kinetic drying coefficients were calculated, and formulas for the drying duration of two- and three-component pellets were obtained.

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Кінетика процесу сушіння композиційних біогранул на конвективному сушильному стенді

Ж. О. Петрова, В. М. Пазюк, Ю. П. Новикова, А. І. Петров

Інститут технічної теплофізики НАН України,
03057, Україна, м. Київ, вул. Марії Капніст, 2а

На сьогодні в Україні існує така проблема, як переповнення мулових карт, до яких постійно додають активний мул, що з часом перетворюється на мулові відкладення. Крім того, накопичені мулові відкладення застарілі, через що вони втратили переважну кількість біогенних речовин, стали занадто мінералізованими й майже непридатними до безпосереднього одержання з них біопалива. Їх ліквідація потрібна для ефективної та безперебійної експлуатації очисних споруд, а також для рекультивації земель. Однак для розв'язання цієї проблеми можна використовувати застарілі мулові відкладення при створенні палива на основі торфу та біомаси, що набуває актуальності через енергетичну кризу у всьому світі. Тому нині нагальним завданням є розробка технології переробки застарілих мулових відкладень на паливні гранули, які можуть використовуватися як паливо для, наприклад, міні-ТЕЦ, що одночасно виробляють теплову й електричну енергію. Зауважимо, що застарілі мулові відкладення мають малий вміст органічної складової, з огляду на це для кращої їх утилізації запропоновано створювати композитні гранули, а отримана при подальшому їх сушінні й спалюванні зола застосовуватиметься для виготовлення будівельних матеріалів. Метою роботи було проведення дослідження процесу сушіння композитних гранул на конвективному стенді й узагальнення результатів теоретичним розрахунком. У роботі вивчені процеси сушіння композиційних гранул на основі застарілих мулових відкладень, торфу й біомаси і визначені ефективні режими сушіння. Виявлено вплив температури теплоносія на тривалість сушіння мулоторфяної композиції: підвищення температури зменшує тривалість сушіння гранул у 1,4 раза. Крім того, при порівнянні кінетики сушіння дво- і трикомпонентних гранул при температурі 80 °С та 120 °С встановлено, що тривалість сушіння трикомпонентних гранул в 1,1–1,4 раза менша, ніж у двокомпонентних, тобто підвищення температури теплоносія зменшує тривалість сушіння трикомпонентних гранул приблизно у 1,5 раза. Теоретичні дослідження, за підсумками яких побудовані узагальнені криві сушіння композиційних гранул, розраховані за до допомогою методу В. В. Краснікова, показали збіг з експериментальними даними. З узагальнених кривих сушіння і швидкості сушіння розраховані відносні й кінетичні коефіцієнти сушіння, отримані формули тривалості сушіння дво- і трикомпонентних гранул.

***Ключові слова**: мулові відкладення, торф, біомаса, гранулювання, біогранули, сушіння.*

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