Determination Of Thermal Technical Characteristics Of Sewage Sludge

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Abstract. One of the largest environmental problems of the Russian Federation is the pollution of the territory waste. The focus is on waste generated during the treatment of urban wastewater - sewage sludge and sewage sludge (SS). The shortage of areas sharply raised the issue of eliminating these wastes. The main elimination method is high temperature combustion. The complex process of elimination requires preliminary heat engineering studies of sewage sludge. In the scientific work, gas-analytical studies of flue gases were carried out, the experimental process of preliminary drying of sewage sludge was reproduced, and calorimetric tests of specific samples of precipitation were calculated with recalculation to the lower calorific value.

1. Introduction
Precipitation of urban sewage sludge has large volumes, very high humidity, heterogeneous composition and properties, contain organic substances that can quickly decompose and decay. The main advantage of the high-temperature liquidation of sewage sludge is a significant reduction in their mass (by about 75%) and volume (up to 90%), which is especially important in the face of a shortage of free space for organizing landfills and landfills. When burning, many hazardous organic compounds decompose, and the use of heat generated to produce electricity and ash and slag residues for the production of certain materials may partially offset the cost of waste processing. These heat engineering studies will allow us to competently and rationally organize further processes for the disposal and elimination of waste.

2. Researches of smoke gases from burning of SS samples by using a gas analyzer
2.1. General information
In this scientific work, experimental studies were carried out to study and analyze the composition of exhaust house gases for the content of O2, CO, CO2, NOx and the excess air index after thermal treatment of SS from 4 different aeration stations in Moscow and the Moscow region. We used a gas analyzer of the MRU Vario Plus model, shown in figure 1. Vario Plus gas analyzer is a semi-stationary monitoring multifunctional system for industrial measurements. It is used in the manufacture of glass, brick, ceramics, for setting up burners, diesel generators and boilers of any size,
operating on any type of fuel - gaseous, liquid and solid. The device can take measurements in automatic mode for several days.

Gas analyzer functions:
- Long-term measurements and control tests of industrial plants;
- Performance tests and commissioning of gas oil burners;
- Emission analysis of fuel combustion devices of all types;
- The combination of infrared technology and electrochemical sensors, which gives the highest accuracy of measurement results [1].

Figure 1. Gas analyzer "MRU Vario Plus", presented at the Department of Computer Technology NRU "MPEI"

In the electric oven "Nabertherm HT 04/17", presented on the 1st floor of the Department of Energy of High-Temperature Technology NRU "MPEI", the samples were heated from 40 °C to 1000 °C. The time of each experiment was 1 hour 40 minutes [2]. Table 1 presents the initial data on the composition of sediment samples.

Table 1. The initial composition of the wet sediment, %.

| №  | Sediment                | Source of sediment          | The composition of the working mass, % |
|----|-------------------------|------------------------------|---------------------------------------|
|    |                         |                             | W<sub>W</sub> | A<sub>W</sub> | H<sub>W</sub> | C<sub>W</sub> | N<sub>W</sub> | O<sub>W</sub> | S<sub>N</sub> |
| I  | Zelenograd aeration station<sup>b</sup> | 6,31 | 82,19 | 1,23 | 6,62 | 0,61 | 2,83 | 0,21 |
| II | Lyubertsy aeration station | 92,0 | 1,94 | 0,51 | 3,61 | 0,31 | 1,59 | 0,04 |
| III| Station of aeration Southern Butovo<sup>a</sup> | 90,0 | 3,62 | 0,51 | 3,7 | 0,44 | 1,65 | 0,08 |
| IV | Kuryanovskaya aeration station<sup>a</sup> | 87,0 | 6,61 | 0,43 | 3,55 | 0,36 | 1,94 | 0,11 |

<sup>a</sup> Precipitation samples from the city of Moscow were taken from the primary sedimentation tank; they are a fluid suspension.

<sup>b</sup> A sample of the sediment from Zelenograd was taken after a coarse screen (mixture with sand).

<sup>c</sup> It is an almost loose powder (or dried paste). Experiments in the Department of ChEE NRU "MPEI" using the SNOL 58/350 oven.

2.2. Sample studies from Zelenograd aeration station

Table 2 presents the initial mass of the crucible and sediment, as well as the resulting mass of ash after high-temperature neutralization of SS.
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**Table 2.** The mass of the first sample, g.

| $M_C$  | $M_{C+SS}$ | $M_{SS}$ | $M_{C+ASH}$ | $M_{ASH}$ |
|--------|------------|----------|-------------|-----------|
| 16,8   | 28,1       | 11,3     | 26,4        | 9,6       |

During the research work, 13 measurements of the composition of the flue gases by a gas analyzer were made. Data on the composition of flue gases after burning the sludge from Zelenograd treatment plants are presented in table 3.

During the first experiment, it was found that the maximum yield of CO and CO2 falls at 370 ºC, and at 800 ºC the release of CO ceases altogether, which leads to the complete oxidation of the organic part of the sample.

**Table 3.** Composition of flue gases after burning SS from Zelenograd treatment facilities.

| t (°C) | $O_2$ (％) | $CO_2$ (％) | CO (ppm) | NO$_x$ (ppm) | NO (ppm) | excess air |
|--------|------------|------------|----------|--------------|----------|------------|
| 1      | 130        | 21         | 0        | 3            | 0        | 0          |
| 2      | 200        | 20,9       | 0,1      | 143          | 2        | 2          | 60,5       |
| 3      | 300        | 20,2       | 0,6      | 0,141%       | 6        | 6          | 26,98      |
| 4      | 370        | 19,6       | 1,3      | 0,252%       | 11       | 10         | 15,85      |
| 5      | 400        | 19,7       | 1,2      | 0,207%       | 8        | 7          | 17,23      |
| 6      | 500        | 19,9       | 1,1      | 0,072%       | 9        | 8          | 19,57      |
| 7      | 560        | 20,3       | 0,9      | 177          | 14       | 16         | 23,68      |
| 8      | 600        | 20,2       | 0,9      | 70           | 18       | 17         | 26,32      |
| 9      | 700        | 20,3       | 0,7      | 14           | 20       | 19         | 30,07      |
| 10     | 740        | 20,3       | 0,8      | 6            | 14       | 14         | 31,22      |
| 11     | 800        | 20,3       | 0,9      | 0            | 10       | 10         | 31,38      |
| 12     | 900        | 20,3       | 0,6      | 0            | 10       | 10         | 31,73      |
| 13     | 1000       | 20,3       | 0,4      | 0            | 10       | 10         | 31,35      |

2.3. Studies of a sample from the Lyubertsy treatment facilities

Table 4 presents the initial mass of the crucible and sediment, as well as the resulting mass of ash after high-temperature neutralization of SS.

**Table 4.** The mass of the second sample, g.

| $M_C$  | $M_{C+SS}$ | $M_{SS}$ | $M_{C+ASH}$ | $M_{ASH}$ |
|--------|------------|----------|-------------|-----------|
| 18,6   | 32,1       | 13,5     | 19,1        | 0,5       |
During the research work, 13 measurements of the composition of the flue gases by a gas analyzer were made. Data on the composition of flue gases after burning sludge from the Lyubertsy treatment facilities are presented in table 5.

During the second experiment, it was revealed that the maximum yield of CO occurs at 400 °C, CO2 at 500 °C, and at 800 °C, the CO emission temporarily ceases, but from 900 °C to 1000 °C the remaining organic part of the sediment is burned out.

Table 5. Composition of flue gases after burning SS from Lyubertsy treatment facilities.

| t, °C | O2, % | CO2, % | CO, ppm | NOx, ppm | NO, ppm | excess air |
|------|-------|--------|---------|----------|---------|------------|
| 1    | 130   | 20,9   | 0,1     | 0        | 1       | 1          |
| 2    | 200   | 20,9   | 0,2     | 3        | 1       | 1          | 0          |
| 3    | 300   | 20,8   | 0,2     | 493      | 6       | 6          | 0          |
| 4    | 370   | 20,3   | 0,5     | 0,23%    | 13      | 13         | 32,79      |
| 5    | 400   | 20,0   | 0,9     | 0,379%   | 25      | 24         | 20,03      |
| 6    | 500   | 19,5   | 2,1     | 0,094%   | 44      | 42         | 14,2       |
| 7    | 560   | 19,9   | 1,6     | 109      | 48      | 45         | 19,79      |
| 8    | 600   | 20,1   | 1,5     | 54       | 49      | 46         | 23,77      |
| 9    | 700   | 20,3   | 0,5     | 8        | 22      | 21         | 31,8       |
| 10   | 740   | 20,5   | 0,3     | 2        | 14      | 13         | 45,65      |
| 11   | 800   | 20,6   | 0,1     | 0        | 9       | 9          | 31,38      |
| 12   | 900   | 19,8   | 0       | 3        | 11      | 10         | 31,73      |
| 13   | 1000  | 20,6   | 0       | 20       | 14      | 13         | 31,35      |

2.4. Studies of a sample from the South Butovo treatment facilities

Table 6 presents the initial mass of the crucible and sediment, as well as the resulting mass of ash after high-temperature neutralization of SS.

Table 6. The mass of the third second sample, g.

| M_C | M_C+SS | M_SS | M_C+ASH | M_ASH |
|-----|--------|------|---------|-------|
| 17,4| 34,2   | 16,8 | 17,8    | 0,4   |

During the research work, 13 measurements of the composition of the flue gases by a gas analyzer were made. Data on the composition of flue gases after burning sludge from the South Butovo treatment facilities are presented in table 7.

In the course of the third experiment, it was revealed that the maximum yield of CO occurs at 500 °C, CO2 at 560 °C, and at 740 °C the emission of CO ceases altogether, which leads to the complete oxidation of the organic part of the sample.
Table 7. Composition of flue gases after burning SS from South Butovo treatment facilities.

| t (ºC) | O₂ (%) | CO₂ (ppm) | CO (ppm) | NO (ppm) | NOx (ppm) | excess air |
|-------|--------|-----------|----------|--------|----------|-----------|
| 1     | 130    | 20,9      | 0,2      | 0      | 1        | 1         | 0         |
| 2     | 200    | 20,9      | 0,2      | 1      | 1        | 1         | 0         |
| 3     | 300    | 20,9      | 0,2      | 40     | 3        | 3         | 0         |
| 4     | 370    | 20,8      | 0,2      | 329    | 7        | 6         | 0         |
| 5     | 400    | 20,6      | 0,3      | 0,113% | 14       | 13        | 58,7      |
| 6     | 500    | 20,4      | 0,8      | 0,227% | 35       | 33        | 35,64     |
| 7     | 560    | 19,4      | 2,6      | 0,061% | 68       | 64        | 13,43     |
| 8     | 600    | 19,7      | 1,8      | 50     | 19       | 18        | 17,32     |
| 9     | 700    | 20,2      | 1        | 3      | 22       | 21        | 31,8      |
| 10    | 740    | 20,3      | 0,8      | 0      | 11       | 10        | 29,67     |
| 11    | 800    | 20,3      | 0,5      | 0      | 9        | 9         | 34,24     |
| 12    | 900    | 20,6      | 0,2      | 0      | 7        | 7         | 60,97     |
| 13    | 1000   | 20,7      | 0,1      | 0      | 9        | 9         | 0         |

2.5. Studies of a sample from the Kuryanovsky treatment facilities

Table 8 presents the initial mass of the crucible and sediment, as well as the resulting mass of ash after high-temperature neutralization of SS.

Table 8. The mass of the third fourth sample, g.

| M_C | M_C+SS | M_SS | M_C+ASH | M_ASH |
|-----|--------|------|---------|-------|
| 17,4| 38,8   | 11,4 | 17,7    | 0,3   |

During the research work, 13 measurements of the composition of the flue gases by a gas analyzer were made. Data on the composition of the flue gases after burning the sludge from the Kuryanovsky treatment facilities are presented in table 9.

During the fourth experiment, it was revealed that the maximum yield of CO occurs at 400 ºC, CO₂ at 500 ºC, and at 800 ºC the emission of CO ceases altogether, which leads to the complete oxidation of the organic part of the sample.
Table 9. Composition of flue gases after burning SS from Kuryanovsky treatment facilities.

| t   | O₂ | CO₂ | CO  | NOₓ | NO | excess air |
|-----|----|-----|-----|-----|----|------------|
| °C  | %  | %   | ppm | ppm | ppm|            |
| 1   | 130| 20,9| 0,1 | 0   | 1  | 1          | -           |
| 2   | 200| 20,9| 0,2 | 2   | 2  | 2          | 0           |
| 3   | 300| 20,7| 0,3 | 258 | 6  | 6          | 0           |
| 4   | 370| 20,6| 0,4 | 545 | 9  | 9          | 55,9        |
| 5   | 400| 20,4| 0,4 | 0,1295% | 14 | 14       | 39,38       |
| 6   | 500| 19,9| 1,2 | 0,092% | 40 | 38       | 20,83       |
| 7   | 560| 20,2| 0,9 | 88  | 58 | 56        | 26,45       |
| 8   | 600| 20,3| 0,6 | 32  | 39 | 31        | 32,4        |
| 9   | 700| 20,6| 0,2 | 9   | 12 | 12        | 52,35       |
| 10  | 740| 20,6| 0,2 | 6   | 8  | 8         | 62,89       |
| 11  | 800| 20,7| 0,1 | 0   | 7  | 7         | -           |
| 12  | 900| 20,6| 0,1 | 0   | 6  | 6         | -           |
| 13  | 1000|20,6| 0,1 | 0   | 6  | 6         | -           |

Conclusion: The data obtained are necessary for making a decision on the efficiency and feasibility of burning and subsequent purification of flue gases from harmful impurities. The main emission of carbon monoxide (CO) from the disposal of SS falls into the temperature range 370-500 °C, which is shown in figure 2.

![Figure 2. Graph of the concentration of CO on the heating temperature.](image)

3. Experimental study of thermal drying sewage sludge

3.1. General information
Thermal drying is a technology that aims to drastically reduce the moisture content of sewage sludge. Drying is mainly used in large wastewater treatment plants to increase the calorific value of sludge
during its subsequent combustion. Drying is possible if sludge is used in agriculture, but this method is used infrequently due to its high cost. Evaporation of moisture from the treated and dehydrated sludge leads to an increase in the dry matter content, a decrease in the volume and mass of the sludge. The dry matter content in the dehydrated precipitate before drying, as a rule, is 20–30%, after drying - 50–90% [3].
Thermal drying usually involves the step of loading and unloading sludge, as well as intermediate storage. It is preceded by dehydration and sludge accumulation in the hopper. Thermal drying requires heat production and distribution equipment, a thermal dryer, a biological filter for flue gas treatment, a post-treatment device (for example, a granulation plant) and a final product storage.
In the research work we used the low-temperature Snol 58/350 furnace (figure 3) with forced air convection, presented at the Department of Chemistry and Electrochemical Energy NRU "MPEI".

3.2. Thermal Drying Experimental Studies
Thermal drying of the sludge is usually the final step in the processing of the sludge or the stage of preparing the sludge for liquidation by burning it. In the drying process, disinfection and reduction of the mass of sewage sludge occur. In this research work, we used four samples of sewage sludge from wastewater treatment plants in Moscow and the Moscow Region, the initial weights are presented in table 10. In the Snol 58/350 low-temperature furnace, an analytical study of SS drying in a research laboratory was carried out. Samples of precipitation were heated to 150 degrees Celsius and every 30 minutes the mass of WWS was measured on an Adventurer electronic balance, the experimental results are shown in table 11.

| № | M_BOWL, g | M_BOWL+SS, g | M_SS, g |
|---|----------|-------------|--------|
| 1 | 17,793   | 31,226      | 13,433 |
| 2 | 18,003   | 31,026      | 13,023 |
| 3 | 18,675   | 38,104      | 19,429 |
| 4 | 17,644   | 29,116      | 11,472 |

Sample No. 1, from the Zelenograd sewage treatment plants, had a large number of suspended (coarse) impurities (sand), already in the middle of the experiment, the mass indications ceased to give the dynamics of changes. The percentage of residual precipitate after drying was 93.695%; only 6.305% of moisture was evaporated (Table 12). The Lyubertsy sample (No. 2) lost almost 43.554% of moisture in the first 30 minutes of the experiment and an additional 48.360% in the next 4 hours of the
experiment. Sludge from the S. Butovsky (No. 3) treatment facilities showed more uniform indicators of mass change, which ultimately led to a loss of 90.427% of moisture. Dehydration of the Kuryanovsky SS (No. 4) allowed to reduce sludge moisture by 87.431%, the experiment took 120 minutes.

**Table 11. The change in mass of SS samples during drying, g.**

| Time   | M_{SS1}, g | M_{SS2}, g | M_{SS3}, g | M_{SS4}, g |
|--------|------------|------------|------------|------------|
| Initial mas | 13,433     | 13,023     | 19,429     | 11,472     |
| 0,5 ч   | 12,586     | 5,672      | 11,669     | 4,51       |
| 1 ч     | 12,58      | 2,073      | 7,4        | 2,046      |
| 1,5 ч   | 12,571     | 1,09       | 4,064      | 1,455      |
| 2 ч     | 12,571     | 1,073      | 2,405      | 1,442      |
| 2,5 ч   | -          | 1,068      | 1,892      | 1,442      |
| 3 ч     | -          | 1,063      | 1,872      | -          |
| 3,5 ч   | -          | 1,06       | 1,867      | -          |
| 4 ч     | -          | 1,057      | 1,863      | -          |
| 4,5 ч   | -          | 1,053      | 1,86       | -          |

The percentage of evaporated moisture and dry residue are presented in table 12.

**Table 12. The percentage of dried sludge and evaporated moisture.**

|            | 1          | 2          | 3          | 4          |
|------------|------------|------------|------------|------------|
| % of dried sludge | 93,695     | 8,086      | 9,573      | 12,569     |
| % of evaporated moisture | 6,305      | 91,914     | 90,427     | 87,431     |

Conclusion: After thermal exposure, the sludge is a dry, non-rotting bulk material free of harmful pathogenic microorganisms and ready for further calorimetric tests [4].

4. **Calorimetric tests sewage sludge**

4.1. **General information**

For the proper organization and calculation of heat treatment processes, knowledge of the calorific value of sewage sludge is necessary. The calorific value is the main thermotechnical characteristic of the fuel, determines its energy value and represents the amount of heat released during chemical reactions of oxidation of combustible fuel components with gaseous oxygen.

In this experiment, to determine the calorific value of four SS samples, the calorimeter of the IKA C2000 basic Version 2 model was used, which was presented at the Department of Energy of High-Temperature Technology of NRU “MPEI” (figure 4).
Figure 4. Calorimeter model IKA C2000 basic Version 2:
1 - controller; 2 - keyboard; 3 - display; 4 - electronics unit; 5 - measuring cell; 6 - temperature sensor; 7 - a device for filling oxygen; 8 - a vessel for decomposition; 9 - a cover of a measuring cell.

The calorimetric bomb consists of a thick-walled hermetic cylinder (8) made of special acid-resistant steel and surrounded by a heat-shielding water jacket (its volume is accurately measured). A fuel sample is placed in this cylinder, through a tube (7) connected to the cover, it is filled with oxygen at a pressure of 25-30 atmospheres. A sample with fuel (its mass is precisely known) is located in a cup of quartz or platinum, which stands on a rod fixed to the lid. This rod, together with the fuel sample and the tube, make up a single electrical circuit. When a current is passed through it, the fuel burns out. The energy released as a result of burning the sample is transferred to the water jacket. During the experiment, the temperature rise of the water jacket is measured, which usually does not exceed 1-2 degrees [5].

4.2. Experimental calorimetric studies of SS samples
The experiment was carried out on a pre-dried precipitate. The composition of the pre-dried precipitation is presented in table 13.
Table 13. The initial composition of the dry sediment, %.

| №  | Sediment                  | Source of sediment       | The composition of the working mass, % |
|----|---------------------------|--------------------------|---------------------------------------|
| I  | Zelenograd aeration station | 0                        | 87,7 1,31 7,06 0,69 3,02 0,22          |
| II | Lyubertsy aeration station | 0                        | 24,3 6,36 45,2 3,78 19,98 0,38         |
| III| Station of aeration Southern Butovo | 0            | 36,19 5,1 36,98 4,44 16,53 0,76      |
| IV | Kuryanovskaya aeration station | 0                        | 51,0 3,28 27,44 2,44 15,0 0,84        |

Initially, 4 measurements were made of the mass of the samples on a VIBRA SJ-2200CE laboratory electronic balance (table 14).

Table 14. The initial mass of sediment sludge, g.

|       | M_{SS1} | M_{SS2} | M_{SS3} | M_{SS4} |
|-------|---------|---------|---------|---------|
|       | 3,5     | 0,9     | 0,8     | 0,9     |

In the course of the research work, the obtained data on the calorific value of four samples of SS in Moscow and the Moscow Region are presented in table 15.

Table 15. Experimental data on the calorific value of the samples, MJ / kg.

| Q_{b1} | Q_{b2} | Q_{b3} | Q_{b4} |
|--------|--------|--------|--------|
|        | 16,086 | 17,918 | 13,177 |

Conclusion: due to the large amount of coarse impurities (sand) and the low organic content in the first sample (sediment from Zelenograd sewage treatment plants), the experiment did not give any result. During the experiment, the highest calorific value was revealed in the sediments of the South Butovo treatment facilities, equal to 17.918 MJ / kg [6].

4.3. Conversion of the calorific value of the bomb to the lower calorific value

Net calorific value:

\[ Q_N = Q_b - 24,42 (8,94H + W) \] (1)

Where,

- 24.42 - the heat of vaporization at a measurement temperature of 25 °C based on 1% of the released water, kJ / kg;
- 8.94 - conversion factor of the mass fraction of hydrogen to water;
- H - the mass fraction of hydrogen in the analytical sample of fuel;
- W - mass fraction of water in the test product.
Table 16. Conversion of the calorific value of the samples on the bomb to the higher calorific value, MJ / kg.

|       | $Q_{N1}$ | $Q_{N2}$ | $Q_{N3}$ | $Q_{N4}$ |
|-------|---------|---------|---------|---------|
|       |         | 14,697  | 16,804  | 12,461  |

The obtained calculated data according to the results of the experiment reflect the real indicators of the lower calorific value of the sewage sludge samples. On average, the calorific value of the sediment (three successful samples) varies around 15 MJ / kg. Picture 5 shows a comparative diagram of the values of the calorific value of various fuels with the obtained average value of the calorific value of SS.

![Figure 5: Comparative diagram of the calorific value of some fuels, MJ / kg.](image)

Conclusion: The comparative diagram on Picture 5 demonstrates advantage of the calorific value of precipitation over such fuels as peat, dry firewood and some types of brown coal.

5. Conclusion

Research of sewage sludge in Moscow and the Moscow Region performed at the Department of Energy of High-Temperature Technology of the National Research University “MPEI” are aimed at the subsequent organization of high-temperature waste disposal.

Flue gas analysis shows the maximum yield of carbon monoxide and other harmful gases. These indicators are necessary for further environmental impact assessment and the organization of a proper and effective filtration system.

High-temperature drying is an integral stage in the preparation of precipitation for disposal and elimination. It was experimentally shown that the main percentage of moisture in the precipitate lost in the first hour of the experiment.

Experimental calorimetric studies revealed the energy value of each of the WWS samples or proved the inability of the composition to burn (sediment from the Zelenograd sewage treatment plants). The average calorific value of the remaining three samples approaches 15 MJ / kg.
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