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SEWAGE SLUDGE COMBUSTION – EXPERIMENTAL AND THEORETICAL ANALYSIS

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Whereas the use of biofuels has attracted increasing attention, the aim of this paper is to investigate the possibility of using sewage sludge as biofuel. Preparation of untreated and stabilised sludge with natural additives is described, as well as combusting method applied and experimental results of combusting are presented based on the assessment of composition of emitted pollutants and their concentrations in the exhaust gas. NO_x formation in the exhaust gas has been analysed in depth. The results of investigations have shown that the use of dried sewage sludge possesses a positive energy balance. Therefore, the sludge may be used as fuel. The obtained experimental results demonstrate that during combustion, pollutant concentrations vary depending on oxygen content (O_2), while formation of nitrogen oxides is strongly influenced by fuel-bound nitrogen. Also, a generalized equation of calculating fuel bound nitrogen conversion into NO_x is presented.

Keywords: sewage sludge, combustion, NOx concentration, conversion factor, CO

1. INTRODUCTION

Large quantities of sludge are formed in sewage treatment facilities every year, the majority is stored in sludge sites of sewage treatment facilities and only a small proportion of it is being used. Improved sewage collection systems, which apply modern cleaning and treatment technologies, results in the increasing of quantity of sludge formed during sewage treatment. This treatment means a biochemical process during which compounds of organic substances, with the help of microorganisms and oxygen, are transformed into minerals (Čepanko and Baltrėnas, 2011). The need to introduce sludge treatment technologies, which would allow to reduce the quantity of sludge, and to use treated sludge as a renewable energy resource, increases.

The amount of sewage sludge obtained in sewage treatment plants and its physical and chemical characteristics constitute important problem for the exploiter of these plants. Sludge treatment processes involve more than 30% of the operational costs for the entire wastewater treatment plant (Magdziarz et al., 2011).

Recently production and use of bio-fuel has become the most prospective type of renewable energy production both in Lithuania, and EU countries. In order to reduce the dependence on oil, gas and other types of fossil fuels, and increase the independence in energy sector of a country it is necessary to increase bio-fuel production and its use.

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The extent of sludge use as an energy resource depends on the following factors:

- diminishing quantity of sludge produced in sewage treatment plants,
- harmless final product (ash), if sludge of at least second category is used for combustion,
- it is possible to combust the sand/gravel and oils together,
- it is possible to use excess heat,
- the use of sewage sludge allows to reduce combustion of fossil fuel.

It is possible to reduce the quantity of fuel and receive income from energy production when combusting sewage sludge with fuel or waste (Cartmell et al., 2006). The most important pollutants, which are formed during incineration of fuel, are NO_x, CO, SO_x particulates. Some specific pollutants, such as Cl_2, HCl, salts, dioxins and furanes can be generated during incineration (Magdziarz et al., 2011). The concentration of oxygen (O_2) has the major influence on the composition of flue gases, because the combustion products (soot C, hydrogen H_2, etc.), and the formation of other groups of components (nitrogen and sulphur oxides) depend on it.

One of the main problems of sewage sludge incineration is high quantity of nitrogen compounds contained in it, resulting in formation of high quantity of emitted pollutants NO_x ($NO + NO_2$) and N_2O. Recently N_2O is known as a component, responsible for greenhouse effect (Shimizu et al., 2006). It has been determined that NO_x emission is smaller when combusting wet (mechanically drained) sewage sludge than in case of combusting dry sludge, whereas the primary quantity of nitrogen in wet sludge is higher. Wet sludge contains more ammonium, dissolved (or bound) in the aqueous phase, which helps reducing NO, as it is practiced in SNCR process (Sanger et al., 2001).

Production of NO_x as a result of direct biomass combustion is strongly dependent on thermal formation of NO_x, which involves nitrogen in the air, and emissions are therefore comparable to those of fossil fuel combustion (Čepanko et al., 2010). High quantities of nitrogen oxides form during incineration not only because of a high quantity of nitrogen in sludge, but also because of high quantities of oxides in sludge, particularly ferric oxide, which is frequently used in sludge treatment processes (Shimizu et al., 2006).

Prior to combustion of untreated sewage sludge, it should be mechanically and partially thermally drained. In order to maintain incineration process during combustion of untreated sewage sludge additional fuel is required. Usually biogas, natural gas or solid fuels are used. Additional quantity of fuel depends on many factors, such as kind of sewage sludge, as well as the parameters of furnace, incineration temperature and coefficient of air excess.

In addition to the required additional quantity of fuel, the other disadvantage of wet sludge combustion is large quantity of vapour, emitted during incineration. It increases the amount of emitted fumes, thus resulting in larger treatment facilities for emitted gases and higher fan power. In order to avoid additional fuel for incineration, semi-dried sewage sludge 30 ± 46 % SM, received after thermal drying process should be utilised (Sanger et al., 2001). Burning differently treated sewage sludge and its mixtures with natural additives and subsequent assessment of the combustion process based on analysis of air pollution components present in flue gases has been the aim of the present investigations.

2. EXPERIMENTAL PROCEDURE

Untreated sewage sludge and stabilised sewage sludge (a mixture with primary sludge at the proportion of 50:50 after meta-tanks) have been applied in the experiments. Timber processing waste and peat were used for preparation of samples and tests. The following sample mixtures were formed:

1. stabilized sewage sludge,
2. stabilized sewage sludge with sawdust (ratio 50:50);
3. stabilized sewage sludge with sawdust (ratio 25:75);

4. stabilized sewage sludge with peat (ratio 50:50);
5. untreated sewage sludge.

Pellets were formed of prepared mixtures and dried in a special drying equipment for 14 days under natural conditions. Investigations were performed using biomass combustion stand at Kaunas University of Technology (KTU) Heat and Nuclear Power Engineering Department (Fig. 1).

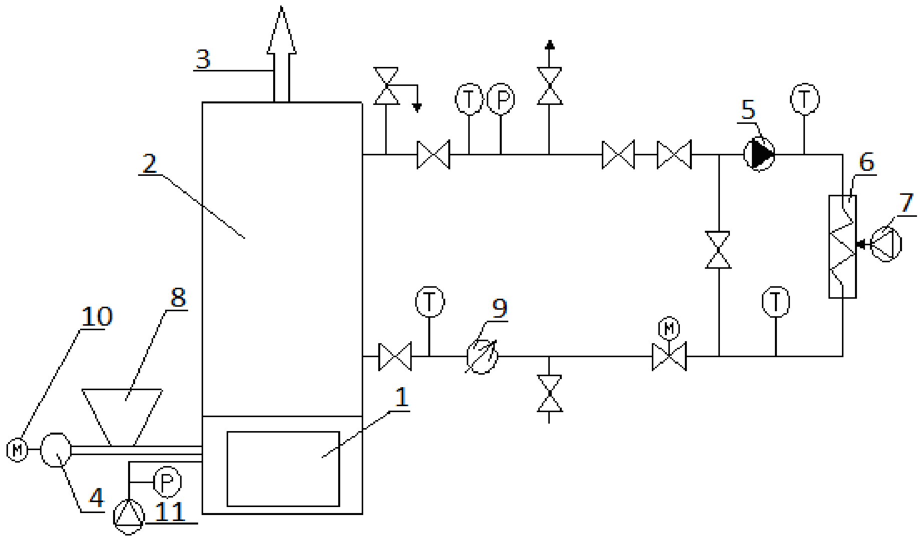

Fig. 1. The main diagram of biomass combustion;
1 – furnace with doors and glass to monitor combustion, 2 – boiler filled with water, 3 – chimney with a sampling port, 4 – reducer, 5 – circulation pump, 6 – heater, 7 – air fan, 8 – fuel tank, 9 – heat measuring system, 10 – electric motor, 11 – air blower supplying air to the combustion chamber

In the system draft is natural and is controlled by a valve installed in the boiler. Burner is installed in a combustion chamber where fuel from a fuel bin is supplied to grids with the help of a screw feeder. Air is drawn from the ambient at temperature of 20 °C, and is supplied to the burner fan support. Then it is divided into two streams – one supplied under the grids, another – above the fuel bed. The experimental run shall start after preheating the system up to 60°C, irrespective of combusted fuel. After a desired temperature in the system has been reached to a desired level, basic experiments are carried out: solid wood pellets combusted, as well as cuts of unusable wood for furniture, charcoal and other separate components. During the experimental runs the temperature and composition of end products of fuel combustion were measured by gas analyzers Ecoline 6000.

In order to calculate the NO_x values and compare them with the measured ones, nitrogen conversion factor was evaluated. In its estimation theoretical quantity of air for combustion, V_0, and theoretical volume of combustion products, V_d, calculated in accordance with the equations (Plečkaitienė and Buinevičius, 2011), depending on the lowest calorific value of fuel, need to be known:

$$V_0 = 0.00027 Q_ž + 0.00234 \tag{1}$$

$$V_d = 0.00025 Q_ž + 0.9756 \tag{2}$$

The ratio of nitrogen conversion into nitrogen oxides is calculated as follows (Buinevičius, 2009):

$$K_N = \frac{(V_d + (\alpha - 1) \cdot V_0) \cdot C_{NO_x}}{328.6 \cdot N_K} \tag{3}$$

Fuel nitrogen conversion factor allows calculating C_{NOx} expressed from formulas 1, 2 and 3:

$$C_{NO_x} = \frac{328.6 \cdot K_N \cdot N_K}{0.358 \cdot Q_{\check{z}} + 0.985} \tag{4}$$

3. RESULTS AND DISCUSSION

During combustion of samples, oxygen concentration in the stack gas amounted from 6 to 19.5 %. The air excess coefficient is an important parameter in combustion process. If insufficient air is supplied, incomplete combustion products form. Uneven fuel mass has been supplied during combustion process thus it might have influenced the composition of gas products. In case of low boiler power, the variations in fuel quantities have significant influence (Čepanko, 2010).

CO and unburned hydrocarbons are emitted to the environment because of the incomplete combustion, which may be caused by excessively low process temperatures, which resulted from flame cooling, too short continuous period of fuel supply insufficient air fed into the combustion chamber, or its high excess, insufficient mixing of fuel and combustion air, resulting in the occurrence of insufficient oxygen available for the process (Buinevičius, 2009).

The quantity of nitrogen oxides in stack gases depends on temperature, quantity of nitrogen in fuel, residence time of combustion products within the flame, and other factors. The characteristics of fuel samples are presented in Table 1.

The highest total nitrogen (N) quantity has been determined in biologically untreated sludge 5.3 % - the lowest in the sample, where the proportions of stabilized sludge and sawdust have been respectively 25 and 75 % - 1.9 %. Relatively high total nitrogen (N) quantity result has been caused by mixing at the proportion of 50:50 with primary sludge.

Table 1. Characteristics of samples

Parameter of research	Sample code* and results				
	1	2	3	4	5
Nitrogen (N) [%]	5.3	3.1	2.9	1.9	4.5
Calorific value [MJ/kg]	15.6	16.8	16.0	17.0	13.9

*1 – untreated sewage sludge , 2 – stabilized sewage sludge with peat (ratio 50:50); 3 – stabilized sewage sludge with sawdust (ratio 50:50); 4 – stabilized sewage sludge with sawdust (ratio 25:75); 5 – stabilized sewage sludge

More air is supplied during fuel combustion than it is theoretically required. The excess of air means that combustion products have air oxygen excess. It is impossible to directly measure air excess, but it may be estimated under the composition of stack gas. Oxygen concentration in stack gas has been from 6 to 19 % and the coefficient of air excess has been from 1.4 to 10.5 during combustion of samples. Such high coefficient of air excess formed because of the leakage of burning chamber and because of the fact that some air for combustion has leaked to the fuel.

During the combustion of stabilized sludge the lowest CO concentration was achieved at 14.3 % concentration of O_2, and increasing the oxygen quantity led to the increase of CO concentration, because air excess leads to the cooling of burning chamber, and in the event of 17.7 % of O_2 CO concentration reached maximum value 7002 mg/m^3. Figure 2 shows dependence of NO_x concentration on the oxygen concentration in combustion gas, thus it is possible to state, that there is not only fuel formation, but thermal NO_x as well. There were changes in oxygen concentration from 11.7 to 18.9 %

during combustion of sample, where the proportions of stabilized sludge and sawdust has been respectively 25 and 75 %. The lowest CO concentration 1373 mg/m³ has been noticed at the minimum value of O_2. In the event of high coefficient of air excess, the highest CO value is reached 7760 mg/m³, because of the overcooling of combustion area.

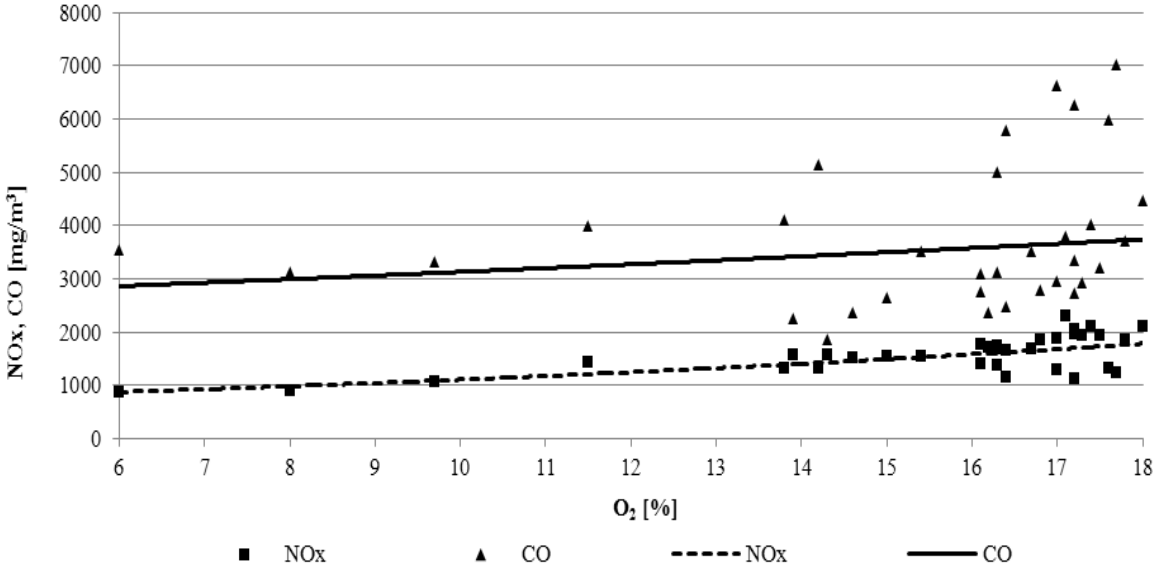

Fig. 2. Exhaust gases composition dependence from oxygen [%] during stabilized sludge combustion

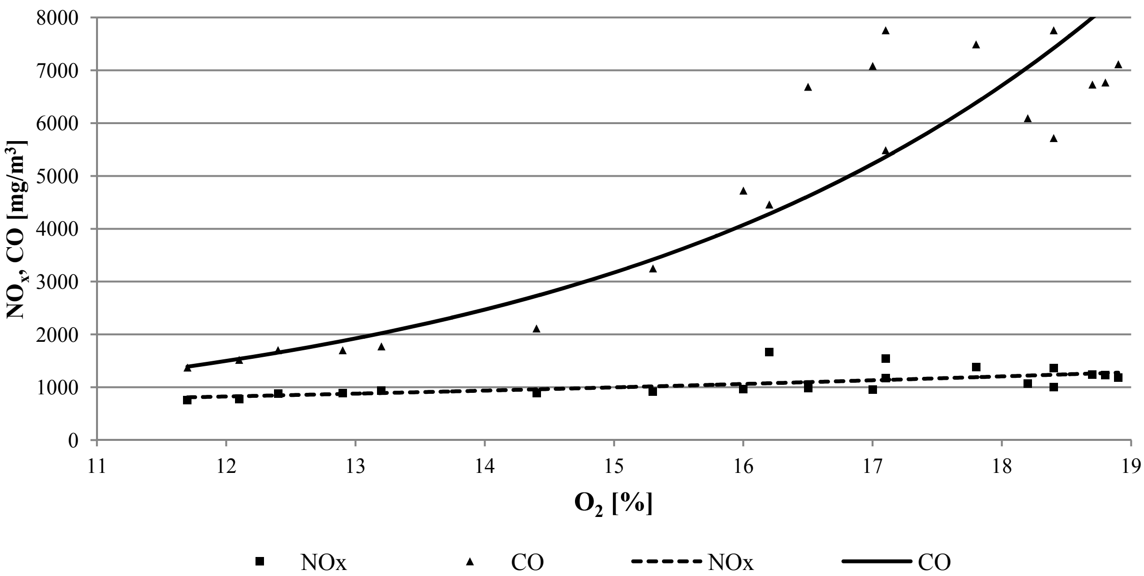

Fig. 3. Exhaust gases composition dependence from oxygen [%] during stabilized sludge and sawdust (ratio 25:75) combustion

As evident from Figure 3, there have been variations in NO_x concentration from 760 to 1667 mg/m³. However, this case shows significant dependence of oxygen concentration. In accordance with the data presented in the table, this sample has the minimum quantity of total nitrogen – 1.9 %. However, NO_x concentrations have not been minimum during combustion, and it was influenced by large quantity of sawdust, which has led to a high temperature of flame. There were changes in O_2 concentration ranging from 15.6 % to 18.8 % during combustion of sample of stabilized sludge and sawdust (ratio 50:50). The minimum CO concentration has been reached at 16.4 %, and the increasing coefficient of air excess has led to the increase in CO value, and it reached maximum value 3613 mg/m³ at the highest O_2 value. However a significant increase of CO practically had no influence on the formation of NO_x.

Variations of NO_x concentration during the entire combustion process of this sample (Fig. 4) have been insignificant and reached from 1462 to 1620 mg/m³. Dependence of NO_x on the coefficient of air excess is imperceptible. Although total nitrogen quantity in this sample was not the highest quantity – 2.9 %, however NO_x concentrations were high. It could have been caused by the formation of thermal NO_x.

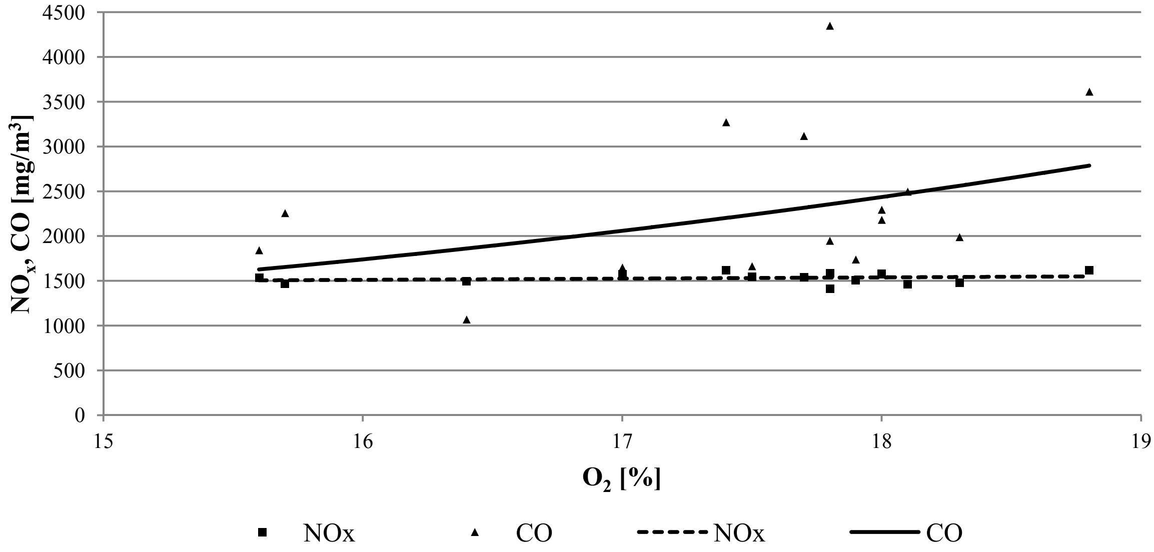

Fig. 4. Exhaust gases composition dependence from oxygen [%] during stabilized sludge and sawdust (ratio 50:50) combustion

There have been changes in O_2 concentration during combustion of stabilized sludge and sawdust (ratio 50:50) sample (Fig. 5). The minimum values of CO concentrations were at 8.3 and 10.2 % of O_2. Maximum CO value 3596 mg/m³ was reached at maximum O_2 concentration 17.2 %.

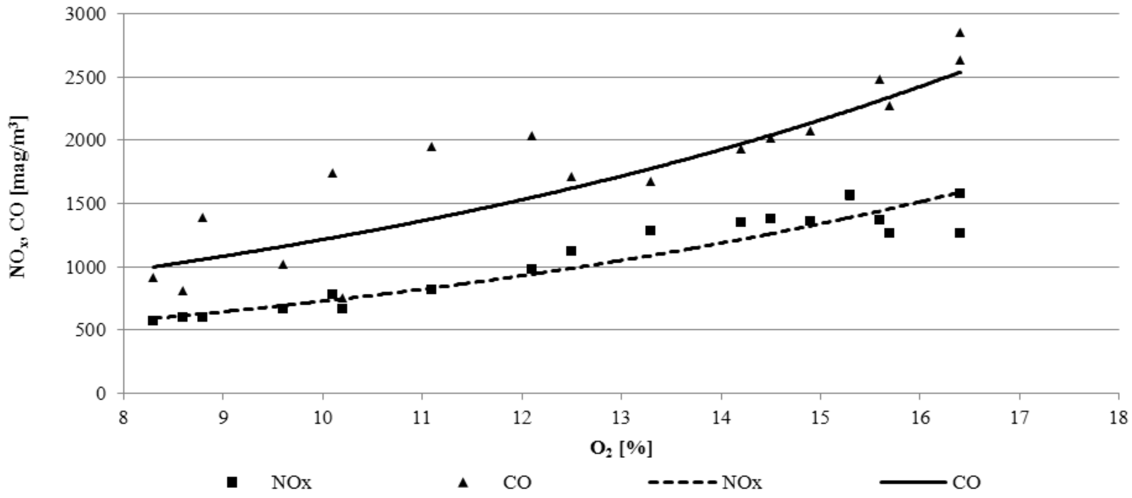

Fig. 5. Exhaust gases composition dependence from oxygen [%] during stabilized sludge and peat (ratio 50:50) combustion

It was determined that there have been changes from 575 to 1576 mg/m³ in nitrogen oxides in this sample. The minimum NO_x concentration was at the minimum O_2 quantity (8.3 %), and the highest value has been reached at 16.4 % quantity of O_2. Such dependence is characteristic to formations of thermal NO_x. The formation of nitrogen oxides has also been influenced by total nitrogen 3.1 % (N) quantity.

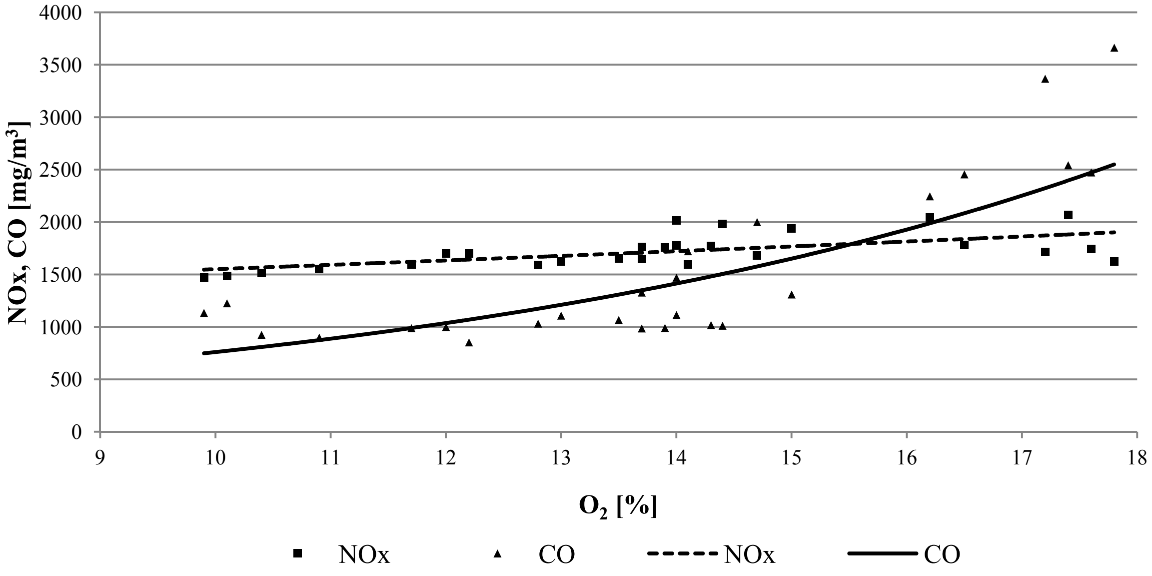

Fig. 6. Exhaust gases composition dependence from oxygen [%] during untreated sludge combustion

There have been changes in oxygen concentration from 9.9 to 17.8 % during combustion of untreated sludge (Fig. 6). The lowest CO concentration has been 851 mg/m³ by O_2 12.2 %, maximum CO value has been 3664 mg/m³ and it was reached at maximum O_2 concentration of 17.8 %. The combustion of this sample shows significant dependence between CO and NO_x values, the increase in CO decreased NO_x concentration and vice versa, the decrease in CO increased NO_x concentration.

It has been determined that there have been changes in NO_x concentration from 1470 to 2071 mg/m³. The highest nitrogen quantity has been reached at O_2 concentration of 17.4 %, and lowest quantity has been reached at 9.9 % O_2. In accordance with the data, presented in Table 1, it is evident that this sample has the highest total nitrogen (N) %, and it caused relatively high NO_x concentrations during combustion.

It has been noticed that CO values (Fig. 7) have been increasing, when increasing oxygen concentration during combustion of all types of fuel, which could have been caused by gasification reaction (Kavaliauskas and Katinas, 2004). CO concentration has been increasing to the maximum value - 7760 mg/m^3, when the excess air has been cooling the combustion area. The minimum CO values have been determined during the combustion of untreated sludge and stabilized sludge with peat (ratio 50:50) - 464 ir 854 mg/m^3. The highest CO concentration has been during the combustion of stabilized sludge with sawdust (ratio 25:75), whereas the particles in fuel were the largest, therefore the air flow to the fuel was the most difficult.

Untreated sludge has not undergone biodegradation process, therefore it contained more biodegradable materials. More volatile gaseous materials have been segregated from this sludge during its combustion which not only burnt well, but also additionally oxidised CO, formed during the combustion of solid part of sludge.

High quantity of nitrogen (N) in sewage sludge was one of the causes, which led to high NO_x concentrations. The sources of nitrogen oxides (NO_x) in stack gas are air molecular nitrogen and nitrogen components of fuel used for combustion. Atomic oxygen, which combines with N_2 and forms NO, occurs at free oxygen quantity and during its dissociation. The chart shows an explicit trend between the dependence of NO_x emission and oxygen concentration, the increase in oxygen quantities results the increase in NO_x concentration.

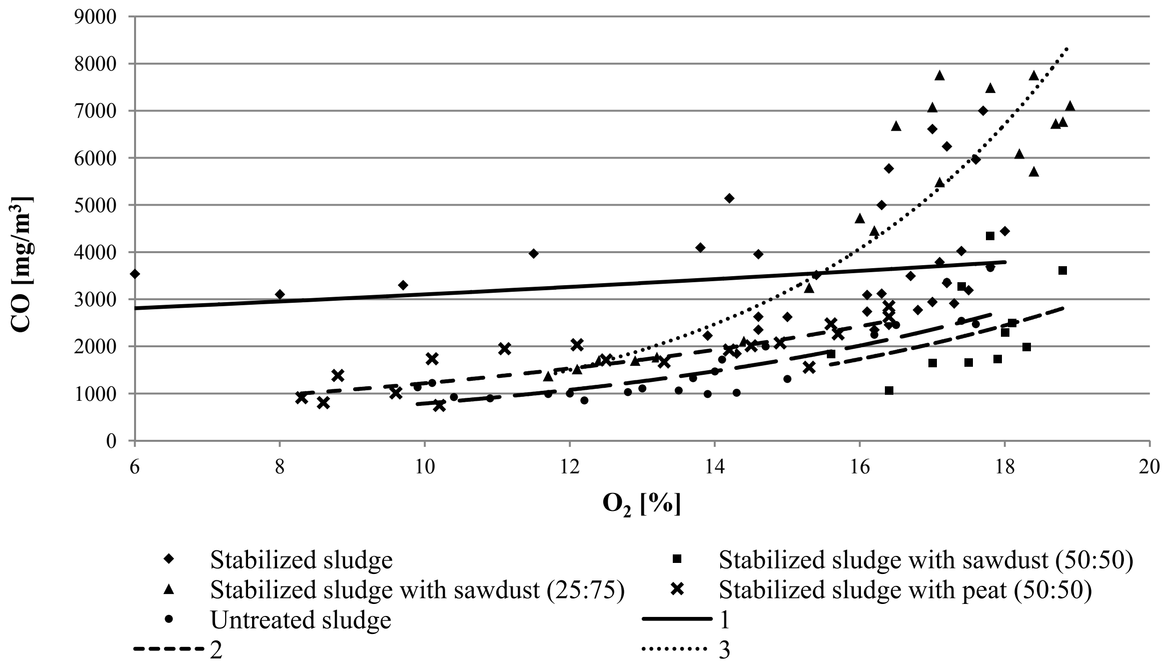

Fig. 7. Variations of CO concentrations in samples;
1 – stabilized sludge, 2 – stabilized sludge with sawdust (ratio 50:50), 3 – stabilized sludge with sawdust (ratio 25:75), 4 – stabilized sludge with peat (ratio 50:50), 5 – untreated sludge

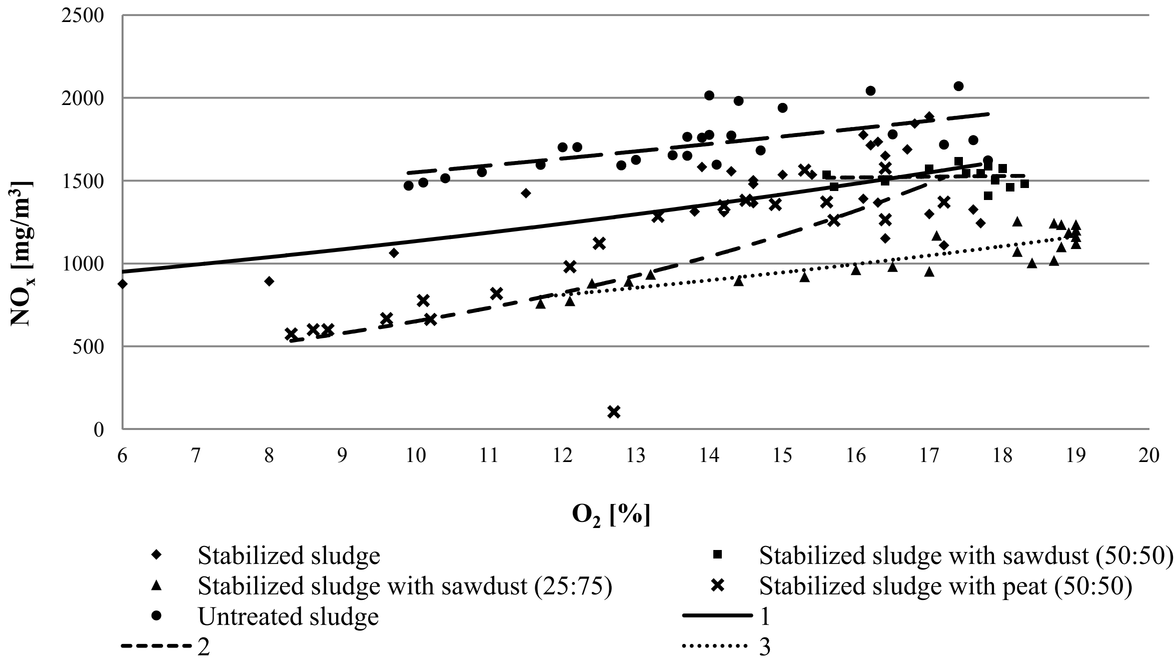

Fig. 8. Variations of NO_x concentrations in samples;
1 – stabilized sludge, 2 – stabilized sludge with sawdust (ratio 50:50), 3 – stabilized sludge with sawdust (ratio 25:75), 4 – stabilized sludge with peat (ratio 50:50), 5 – untreated sludge

The minimum NO_x concentration (Fig. 8) was during the combustion of sample of stabilized sludge and peat (ratio 50:50) 575 mg/m^3, and the highest - 2071 mg/m^3 during the combustion of untreated sludge.

Although the minimum NO_x value has not been reached during the entire test of combustion of mixture of stabilized sludge and sawdust (ratio 25:75), however the maximum NO_x value, received during this combustion, was the lowest 1256 mg/m^3 in comparison with other types of fuel. It was caused by the minimum quantity of nitrogen (N) in the fuel. NO_x values have been relatively high 1410 - 1620 mg/m^3 during the combustion of stabilized sludge with sawdust (50:50), because the fuel was combusting at high quantities of oxygen 15.6 – 18.8 %.

Figure 9 shows evident dependence of NO_x on nitrogen quantity in the fuel. 1.5 - 4 times less energy is needed for nitrogen atoms to be separated from fuel compounds, than for the oxygen molecule to be dissociated, therefore the formation of fuel nitrogen oxides takes place at low temperatures.

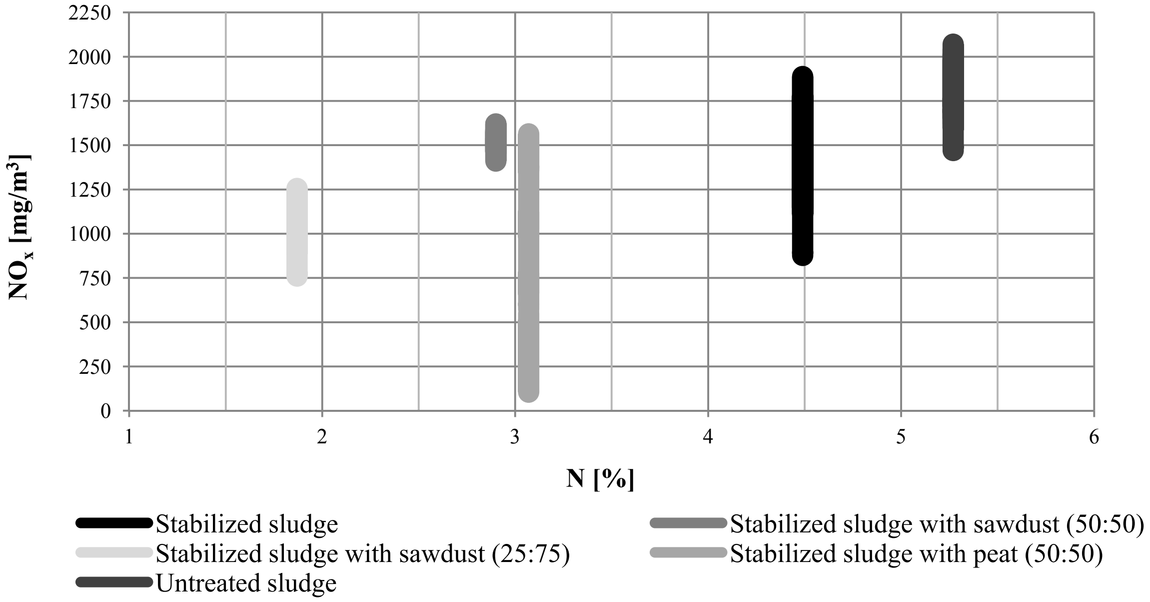

Fig. 9. NO_x dependence from total nitrogen (N) quantity

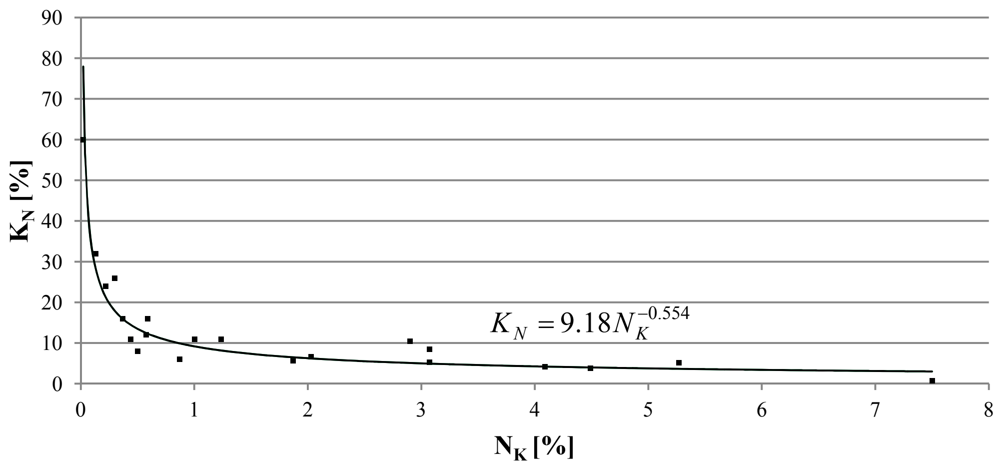

Fig. 10. Fuel nitrogen conversion factor to NO_x dependence of the total nitrogen content in the fuel

The highest nitrogen quantity has been in the sample of untreated sludge, therefore the highest NO_x concentrations 2071 mg/m^3 have been reached in comparison with other samples. The lowest NO_x maximum has been reached during the combustion of fuel containing the minimum nitrogen – the sample of stabilized sludge with sawdust.

K_N was calculated by using the formulas 1, 2, and 3. In accordance with the literature data (Čepanko, 2010; Plečkaitienė and Buinevičius, 2011), the conversion of nitrogen in fuel into NO_x (Fig. 10) has been generalised by the following equation:

$$K_N = 9.18 N_K^{-0.554} \quad (5)$$

After the evaluation of linear dependence of NO_x values on oxygen quantity under the formula 4, we obtain:

$$C_{NO_x} = \frac{3017 N_K^{\ 0.446}}{0.358 Q_ž + 0.985} + 45 O_2 \quad (6)$$

Analysing oxygen concentration influence on conversion of fuel bound oxygen into NO_x, diagram 11 has been obtained. In the diagram, the values of coefficient of nitrogen conversion into NO_x depending on excess air coefficient value have been calculated in accordance with formula (3). It has been established that as excess air amount increases so does fuel bound nitrogen conversion into NO_x.

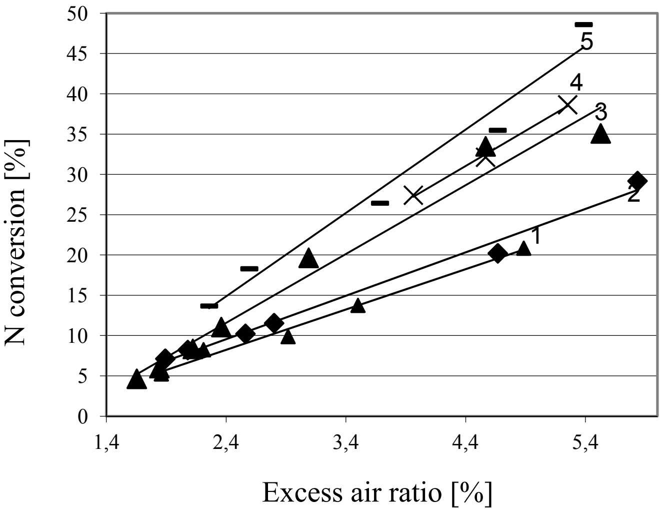

Fig. 11. NOx dependence from excess air ratio;
1 – during combustion stabilized sewage sludge (N_K=5.27 %); 2 – untreated sewage sludge (N_K=4.49 %); 3 – stabilized sewage sludge with peat (ratio 50:50) (N_K=3.07 %); 4 – stabilized sewage sludge with sawdust (ratio 50:50) (N_K=2.9 %); 5 – stabilized sewage sludge with sawdust (ratio 25:75) (N_K=1.87 %)

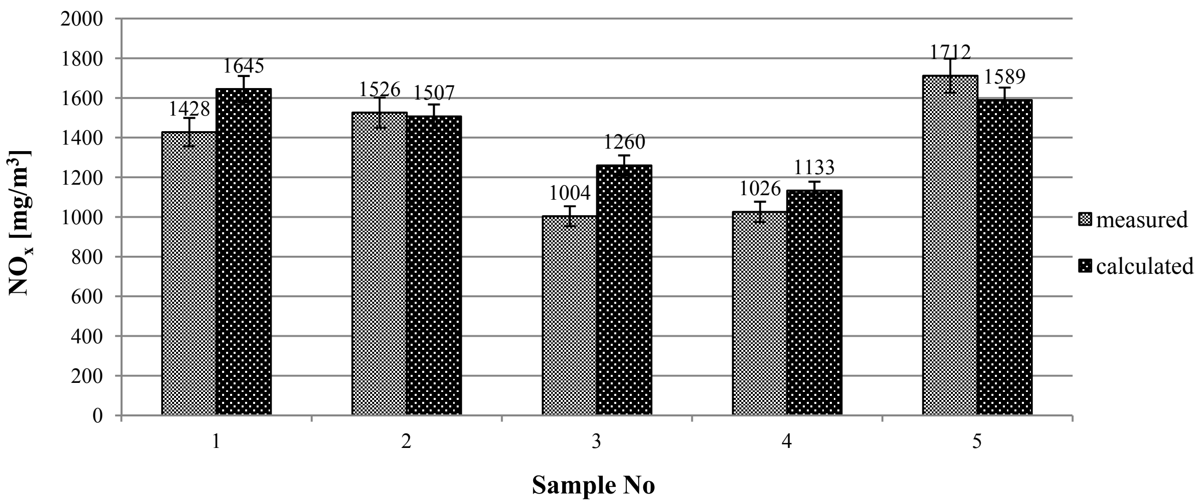

Fig. 12. Average concentrations of NOx, the investigation and the resulting calculations comparison;
1 – stabilized sludge; 2 – stabilized sludge with sawdust (ratio 50:50); 3 – stabilized sludge with sawdust (ratio 25:75); 4 – stabilized sludge with peat (ratio 50:50); 5 – untreated sludge

After the calculation of NO_x concentrations under the formula 6, in accordance with the combustion scenario (at a certain quantity of oxygen), we obtain approximate values, which we compare with the ones obtained during the research (Fig. 12).

The received results differ from concentrations obtained during the experimental combustion of stabilized sludge – 13.2 %, stabilized sludge with sawdust (ratio 50:50) – 1.3 %, stabilized sludge with sawdust (ratio 25:75) – 20.3 %, stabilized sludge with peat (ratio 50:50) – 9.4 %, untreated sludge – 7.7 %.

4. SUMMARY

The tests have shown that in accordance with all scenarios the use of dried sewage sludge has positive energy balance, therefore sludge can be used as fuel. Thermally dried and granulated sludge is a high-quality fuel, which complies with health and safety control requirements, can be easily transported and directly supplied to the incineration plant, without losing its performance potential.

When combusting the samples, the minimum CO concentration has been reached during the combustion of stabilized sludge and sawdust (ratio 50:50) - 851 mg/m³, the highest – during the combustion of stabilized sludge and sawdust (ratio 25:75), and was reaching 7760 mg/m³. The minimum oxygen quantity 6 % has been reached during the combustion of stabilized sludge, and the highest – during the combustion of sludge and sawdust (ratio 25:75), and was reaching 19 %. The highest NO_x concentration has been during the combustion of untreated sludge 2071 mg/m³, and the minimum – in the sample of stabilized sludge and peat (ratio 50:50) 575 mg/m³.

It is necessary to provide technological measures to reduce NO_x emissions when combusting sewage sludge in industrial facilities. The tests showed that NO_x concentration particularly depends on total nitrogen quantity in the fuel.

Research results showed that it is possible to define the conversion of nitrogen in the fuel into NO_x by generalising gradual equation: $K_N=9.18\cdot N_K^{-0.554}$. If the factor of conversion of nitrogen in the fuel is known, it is possible to approximately calculate NO_x concentrations at certain quantity of oxygen.

The results showed that the difference between the measured and received NO_x values is at the average level of 10.4 %.

SYMBOLS

C_{NOx}	concentration of nitrogen oxides in combustion products, mg/m^3
K_N	fuel nitrogen conversion ratio, %
N_K	nitrogen content in fuel, %
$Q_ž$	the lowest value of heat generated by fuel, kJ/kg
O_2	oxygen quantity, %
V_d	teoretical combustion product volume, m^3/kg
V_0	theoretical quantity of air for combustion, m^3/kg
328.6	conversion factor

Greek symbols

α	coefficient of excess air contained in combustion products

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