

# Analysis of solid phase nitrogen conversion process to gaseous oxides

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## 1. Introduction

A particular attention is paid in today's power engineering to those types of fuel that do not cause increase in environmental pollution, reduce dependence on fossil fuels and at the same time on countries exporting this type of fuel and provide conditions for widespread local biofuel use. At present, one of the most promising types of renewable energy sources is biofuel.

On 6 January 2011, a new directive on industrial emissions 2010/75/EU came into force, by which an extremely strict regulation of pollutant emissions had been introduced for boilers over 50 MW capacity. Pollutant concentration rates have become stricter by 2 to 5 times and require new technological solutions. Nitrogen oxide removal from combustion products is the most expensive measure for reduction in pollution caused by exhaust gas, therefore, the topic under investigation is extremely actual, as issue of decrease in NO<sub>x</sub> formation is addressed. The increasing demand for biofuel requires looking for new sources of biofuel, using not applied so far or minutely used types of biofuel that feature stronger concentration of pollutants in combustion products, i.e., high nitrogen content fuels, e. g., poultry litter, some types of grains, straw, other type biowaste, wood-based panels and the like.

As may be seen from scientific literature, numerous research papers prove that a lot of work has been done so far on NO<sub>x</sub> formation and on formation suppression methods [1, 2], still, frequently, research fails to provide scientific data on nature of nitrogen which is the source of these oxide formation. In scientific papers, the issue of NO<sub>x</sub> formation from fuel bound nitrogen has not been sufficiently investigated. In terms of practice, there is no proper methodology for calculation of NO<sub>x</sub> constituent part in fuel, i. e., no possibility exists to predict NO<sub>x</sub> concentration slightly more precisely, even in the case when the nitrogen content in the combusted fuel is known.

The aim of this paper is to investigate patterns of NO<sub>x</sub> formation from fuel bound nitrogen when burning various types of fuel containing nitrogen and investigate possibilities to reduce NO<sub>x</sub> emissions caused by fuel bound nitrogen reducing conversion of the fuel bound nitrogen into nitrogen oxides during fuel combustion process.

## 2. Method and research

The research has been conducted on a test stand for combustion research at Kaunas University of Technology department of Thermal and Nuclear Energy (Fig. 1).

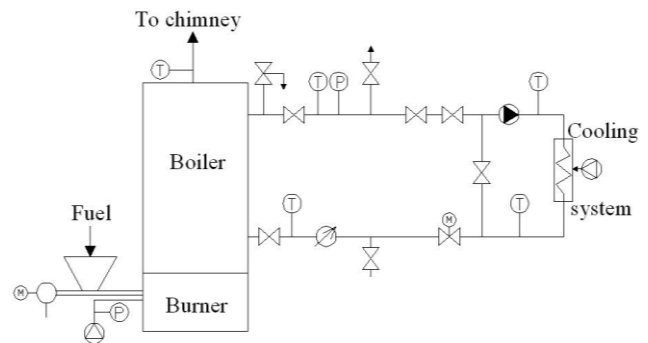


Fig. 1 Principal scheme of biomass research stand

A test stand for biomass burning consists of a furnace with fuel and air supply installations. A boiler is installed above the furnace – a heat exchanger for smoke cooling; combustion products are disposed into the chimney. In the smoke nipple, immediately behind the boiler, a nipple for smoke analysis and temperature measurements is installed. The water, heated in the boiler, is delivered into the cooling system, which consists of a calorifier unit with a cooling fan. The air is supplied into the combustion chamber by means of a fan and distributed into two flows – the primary one that is supplied underneath the grate bars, and the secondary, supplied into the torch above the fuel layer.

During the research, the temperature of the combustion products and their composition (oxygen - O<sub>2</sub>, nitrogen monoxide - NO, nitrogen dioxide - NO<sub>2</sub>, sum of nitric oxide and nitrogen dioxide - NO<sub>x</sub>, sulphur dioxide - SO<sub>2</sub>, hydrocarbons - C<sub>x</sub>H<sub>y</sub>) have been measured employing an analyser ECOLINE 6000. Flame temperature has been measured by an optical thermometer and a thermal couple. Optical thermometer principle is to equalisation the glow of flame or fuel surface to glow of hot filament of thermometer. Was used pyrometer type PROMIN (producer “Kamenec-Podolskij priborostroitelnij zavod” Ukraine) with inaccuracy of this device about  $\pm 30^{\circ}\text{C}$ .

In order to compare the results, the concentration values, obtained during measurements, have been converted into 6% oxygen concentration, as required by biofuel rates, and into 11% oxygen concentration by waste rates.

Different composition fuels have been used for testing requiring different methods of combustion investigation, depending on fuel structure and main parameters. The key parameters of fuels under investigation are provided in the Table.

Table  
Characteristics of investigated fuel types

Fuel type	N quantity, %	Heat generation, kJ/kg
Natural wood pellets	0.130	17025
Stabilized sewage sludge pellets	5.270	15647
Sludge pellets after digestion tank	4.490	13890
Sludge and sawdust (ratio 25:75) blend pellets	1.870	17048
Sludge and sawdust (ratio 50:50) blend pellets	2.900	15995
Sludge and peat (ratio 50:50) blend pellets	3.070	16806
Buckwheat hull	0.574	15912
Crushed packaging (Tetra Pak cartons)	0.021	19451
Wood and poultry litter blend pellets	0.217	16333
Chipped wood (particle board) waste*	3.900	17130
Lignin and mazut (ratio 80:20) blend pellets	0.870	18182
Straw and mazut (ratio 80:20) blend pellets	0.440	15743
Oil waste and straw blend pellets	0.370	17024
Corn stalk pellets	0.590	15617
Corn flour pellets	1.235	14934
Poultry litter and manure blend	3.070	12541

\*They are wood particle boards, composition of which contains binding substances with nitrogen.

### 3. Results

#### 3.1. Research on reduction in fuel NO<sub>x</sub>

The research on wood and biomass combustion has shown [3] a sudden NO<sub>x</sub> jump during the first phase of combustion when the fuel has just been heated and gasification processes take place (Fig. 2). That means that most significant NO<sub>x</sub> are generated during fuel kindling.

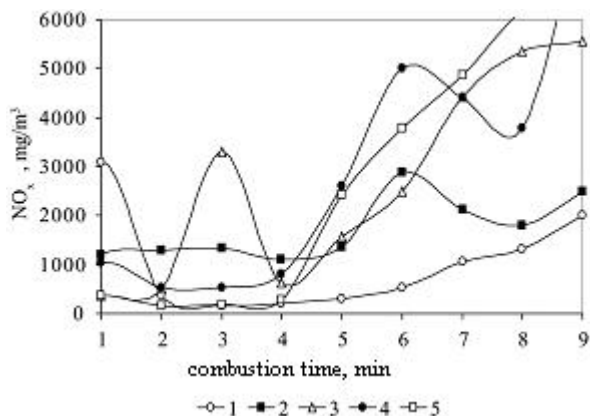


Fig. 2 Time-dependent change in NO<sub>x</sub> concentrations when combusting biomass: 1 – birch firewood; 2 – fruit/vegetables; 3 – poultry manure; 4 – swine manure; 5 – brewer's grains [1]

During the process of biofuel temperature rising, volatile substances are released from fuel, which burn faster than the remainder of solid fuel. The research on combustion product recirculation into the combustion zone with the air supplied for combustion [4] has shown that smoke recirculation reduces formation of NO<sub>x</sub> if the fuel containing nitrogen is burnt gradually, and is just slightly effective when burning takes place without change in air by degrees. This shows indirectly that a part of NO<sub>x</sub> forms from fuel bound nitrogen when gaseous products of fuel pyrolysis are burning.

In order to establish whether the fuel bound nitrogen migrates into gaseous products of fuel pyrolysis, the research has been conducted using chipped wood waste, corn flour pellets and poultry litter and manure blend.

Fuel samples have been heated in closed steel vessels (so that oxygen would not have access and combustion would not take place) in an electric oven for 5 and 10 minutes at different temperatures (300 – 600°C). Afterwards, they have been cooled, weighted and analysed in order to establish nitrogen content. Thus, a nitrogen balance has been created in materials and its distribution at different heating temperatures of samples and different heating periods.

The remained nitrogen content in the fuel depending upon combustion temperature is shown in the results (Fig. 3). Nitrogen content provided in the Table at temperature 0°C means initial nitrogen content in the fuel.

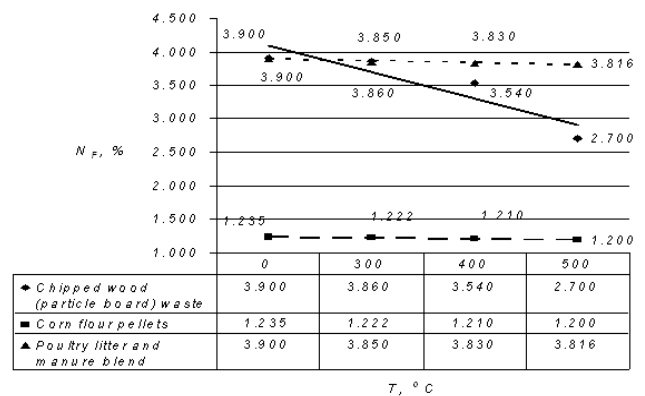


Fig. 3 Change in nitrogen content in the fuel under conditions of fuel sample heating for 5 minutes

The chipped wood waste samples being heated have lost the highest nitrogen content – approximately 31% (Fig. 3). The part of nitrogen in the case of corn flour pellets and poultry litter in the remainder of fuel virtually has remained unchanged.

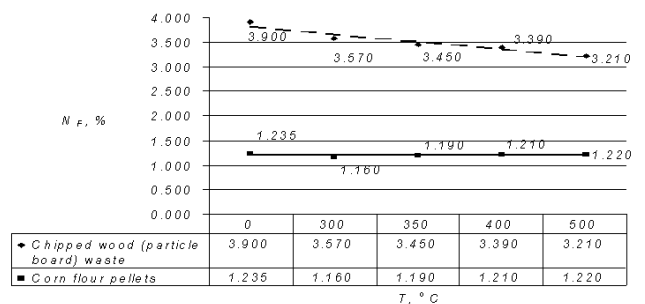


Fig. 4 Change in nitrogen content in the fuel under conditions of fuel sample heating for 10 minutes

When heating the samples for 10 minutes, slightly different results have been obtained, still the fuel has been more pyrolyzed (Fig. 4).

The main reason why the  $N$  releasing from various fuels differs is the different  $N$  chains in raw materials. In the wood plate waste main  $N$  source are urea-formaldehyde resin, in the poultry litter – urea and ammonium salts. Destroying of these are going under lower temperatures than complex aromatic structures where the  $N$  is bonded in the corn flour pellets. In the Figs. 3 and 4 can see nitrogen content in the corn flour pellets remain about the same by heating up to 500°C.

A balance method composed for nitrogen migration from the solid part of the fuel to the gaseous phase (Figs. 5 and 6) has demonstrated that up to 30% of the nitrogen content releases together with gaseous products when fuel undergoes heating up to 500°C, still the greatest part of nitrogen remains in the solid fuel remainder.

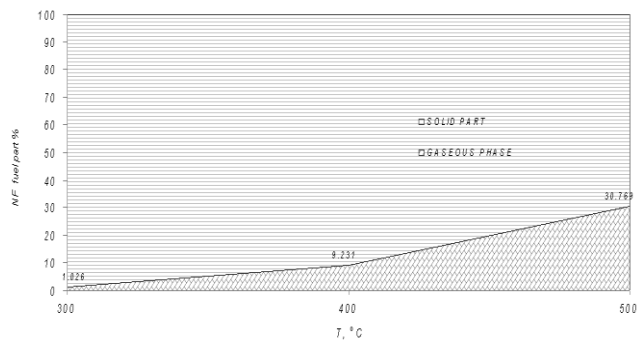


Fig. 5 Nitrogen distribution during fuel temperature rising when heating chipped wood waste for 5 minutes

The research has shown that nitrogen content in the fuel may be reduced by thermal processing. It may be recommended to heat the chipped wood waste for 5 minutes at 500°C. It is not recommended to heat the fuel at temperatures exceeding 500°C, as fuel starts pyrolysing itself. The research has shown that volatile substance removal extent extremely depends on fuel type, therefore, the optimal mode of thermal processing of the fuel should be chosen for each type of fuel.

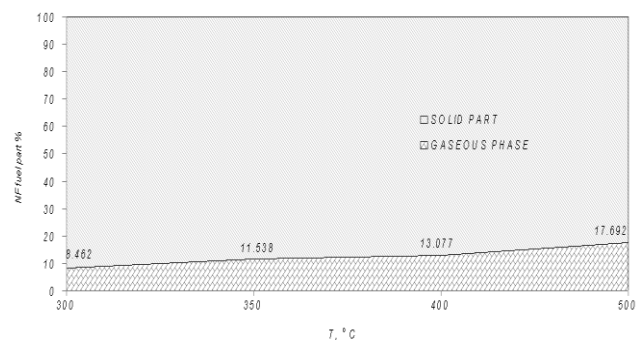


Fig. 6 Nitrogen distribution during fuel temperature rising when heating chipped wood waste for 10 minutes

Fuel thermal processing with volatile substance removal through fuel heating might be a method of reduction in nitrogen content in fuel.

### 3.2. Research on the influence of fuel additives

As a part of nitrogen is disposed from fuel together with volatile substances, the additives could be added to the fuel that would release CO into the combustion zone, while it would compete during the processes of nitrogen oxidation.



where R is radical.

The additives to be added to the fuel should be such that velocities of complete burn would be different, i.e., the CO formed in the combustion products of the additives would release faster than that in the main fuel. Also, the additive should reduce the total content of nitrogen in the combusted fuel.

#### 3.2.1. Research on use of wood coke additive to fuel

Fuel burning with added charcoal also had to reduce the content of nitrogen oxides first of all as fuel without nitrogen compounds. Secondly, the CO formed during coke combustion should reduce NO due to competing reactions. The research has confirmed that coke additives provide additional decrease in NOx (Fig. 7).

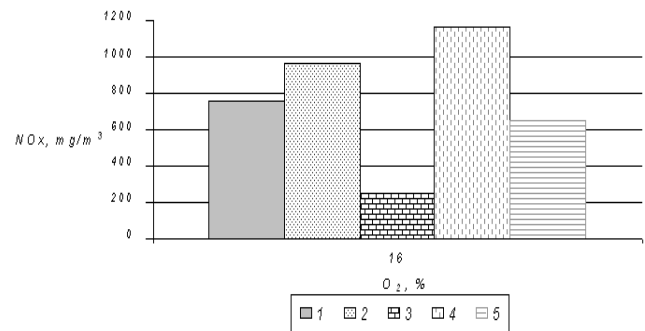


Fig. 7 NOx concentrations under conditions of 16% oxygen in the stoker: 1 – a blend of chipped wood waste, wood pellets and charcoal (ratio 45:45:10),  $N_F = 1.81\%$ ; 2 – a blend of chipped wood waste and wood pellets (ratio 50:50),  $N_F = 2.01\%$ ; 3 – wood pellets,  $N_F = 0.13\%$ ; 4 – chipped wood waste,  $N_F = 3.9\%$ ; 5 – a blend of chipped wood waste and charcoal (ratio 80:20),  $N_F = 3.12\%$

Having added 10% of charcoal to the blend of chipped wood and wood pellets (ratio 50:50), the nitrogen content in the fuel has been reduced by 10%, while NOx concentrations have been lower by approximately 21%. Best evidence for the fact that a role of charcoal as fuel additive for the purpose of reduction in NOx emission is significant, is chipped wood waste and charcoal blend (ratio 80:20) combusting when  $N_F$  decreases by 20%, while NOx concentrations decrease by even 44% (from 1160 to 650 mg/m<sup>3</sup>).

#### 3.2.2. Research on blending the high nitrogen content fuel with “pure” fuel

Chipped wood waste possess a considerable ni-

nitrogen content (3.9%), therefore, using this type of fuel it has been sought to find out what factors influence concentration of nitrogen oxides in combustion products. When combusting this type of fuel, NOx concentrations reached 1000-1250 mg/m<sup>3</sup>.

Combusting of fuel together with other type - "pure" - fuel of low nitrogen content, has taken place blending the chipped wood waste with wood pellets and buckwheat hulls. The previous research had shown [5], that, when burning the above fuels, a small content of nitrogen oxides releases, therefore, their blending with wood waste not only would reduce the total nitrogen content in combusted fuel, but pollutant emissions in combustion products should decrease as well.

When burning the blend of chipped wood waste and wood pellets, the nitrogen content in the blend decreased by 48%, while in this case the NOx content in combustion products decreased by 16% (Fig. 8).

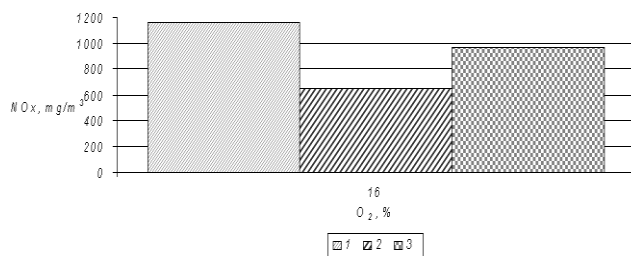


Fig. 8 NOx concentrations under conditions of 16% oxygen in the stoker: 1 - chipped wood waste,  $N_F = 3.9\%$ ; 2 - chipped wood waste and buckwheat hull (ratio 50:50),  $N_F = 2.24\%$ ; 3 - chipped wood waste and wood pellets (ratio 50:50),  $N_F = 2.01\%$

Having blended the chipped wood waste with buckwheat hulls of low nitrogen content, the nitrogen content in the fuel blend has decreased markedly (42%), still fuel combustion has worsened. Both wood waste and buckwheat hulls are of fine and light structure. After the fuels have been blended, it become complicated to regulate the content of air in the stoker, and obtaining a wide range of oxygen has not been successful. NOx concentrations when burning the blend have decreased by 44% (Fig. 8).

Agreeably to nitrogen content in the blend with wood pellets, NOx concentrations should have been lower by 5%. Still, the results have shown that not only nitrogen content in the fuel is a determining factor, but also other factors, maybe volatile substance content in the fuel. This would explain why, when burning the blend with buckwheat hulls, NOx has been lower by 32% than when burning a blend with wood pellets.

When burning the blend of chipped wood waste of high nitrogen content with „clean“ wood pellets of low nitrogen content, the decrease in NOx concentration, identified by calculation formula 9 and diagram Fig. 13 [7], should have reached 43%, still actually decreased by 16% only. This could mean that fuel bound nitrogen conversion into NOx has increased and this method of reduction in NOx is not effective.

The research has shown that a part of substances containing nitrogen releases from fuel together with the volatile substances during fuel temperature rising. When heating the fuel up to 500°C, the nitrogen content of up to 30% releases together with gaseous substances. N content

in the fuel may be reduced by thermal processing of the fuel.

Fuel additives generating CO decrease NOx formation.

Blending the high nitrogen content fuel with the „pure“ fuel, NOx concentration in combustion products depends not only on nitrogen content in the blend, but also on what fuel it is blended with. The results are determined not only by nitrogen content in the fuel, but also by some other factors, maybe by content of volatile substances in the fuel.

### 3.3. Research on the Factor of Fuel Bound Nitrogen Conversion into NOx

The influence of nitrogen content in the fuel on NOx concentration in combustion products is known [6], still, in order to prepare a method for calculation of NOx concentration from fuel bound nitrogen, more detailed investigation is required.

The research has been conducted burning biofuel of various types, waste and fuel blends (Table). In diagrams (Figs. 9 and 10) dependencies of NOx concentrations, measured during experiments, on nitrogen content in the combusted fuel are provided.

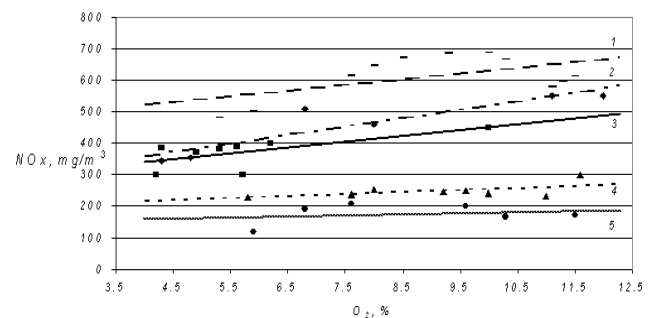


Fig. 9 NOx dependence from oxygen during biomass fuel combustion: 1 - corn flour pellets ( $N_F = 1.235\%$ ); 2 - corn stalk pellets ( $N_F = 0.59\%$ ); 3 - buckwheat hull ( $N_F = 0.574\%$ ); 4 - wood and poultry litter blend pellets ( $N_F = 0.217\%$ ); 5 - wood pellets ( $N_F = 0.067\%$ )

Fig. 10 shows dependencies of NOx concentrations for mixed composition fuels.

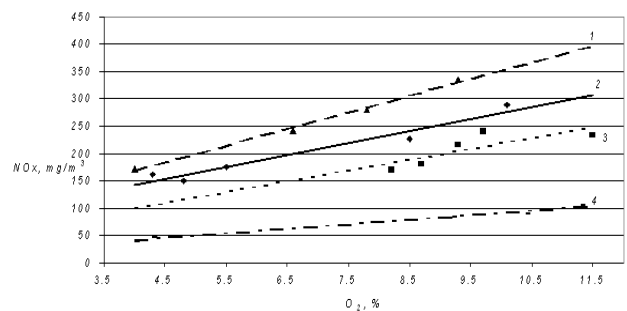


Fig. 10 NOx dependence from oxygen during waste: 1 - oil waste and straw blend pellets ( $N_F = 0.37\%$ ); 2 - lignin and mazut (ratio 80:20) blend pellets ( $N_F = 0.87\%$ ); 3 - straw and mazut (ratio 80:20) blend pellets ( $N_F = 0.44\%$ ); 4 - crushed packaging (Tetra Pak cartons) ( $N_F = 0.021\%$ )

$K_N$ , the factor of fuel bound nitrogen conversion into nitrogen oxides, has been calculated as a part of fuel bound nitrogen, which has migrated to NOx, by equations provided in literature sources [7]:

$$K_N = \frac{(V_d + (\alpha - 1)V_o)C_{NOx}}{328.6N_F} \quad (3)$$

where  $K_N$  is fuel nitrogen conversion ratio, %;  $\alpha$  is coefficient of excess air contained in combustion products;  $C_{NOx}$  is concentration of nitrogen oxides in combustion products, mg/m<sup>3</sup>;  $N_F$  is nitrogen content in fuel, %; 328.6 is conversion factor;  $V_o$  is theoretical air, m<sup>3</sup>/kg:

$$V_o = 0.00027Q_Z + 0.0235; \quad (4)$$

$V_d$  is theoretical combustion product volume, m<sup>3</sup>/kg:

$$V_d = 0.00025Q_Z + 0.9756, \quad (5)$$

where  $Q_Z$  is the lowest value of heat generated by fuel, kJ/kg.

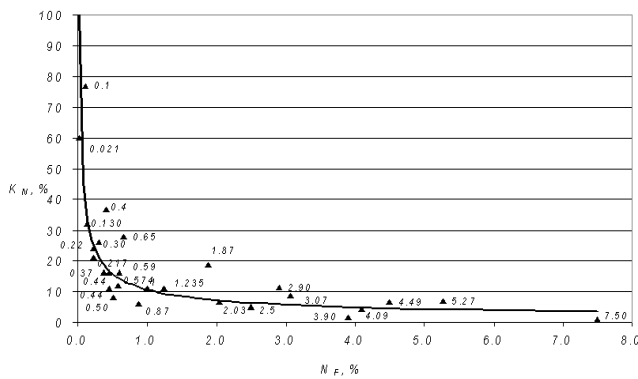


Fig. 11 A part of fuel bound nitrogen that has migrated to nitrogen oxides when burning fuel with various nitrogen contents: point 0.021 obtained during combustion of shredded packs; point 0.130 – during combustion of wood pellets; points 0.1; 0.4; 0.65 – during combustion in stend of KTU of kerosene with pyridine ( $C_5H_5N$ ) additives [8]; points 0.22; 0.44 – during combustion in stend of KTU of natural gas with karbamide additives [8]; point 0.217 – wood and poultry litter blend pellets; points 0.3; 0.5; 1.0 and 2.5 wood pellets with karbamide; 0.37 – oil waste and straw blend pellets; 0.44 – straw and mazut (ratio 80:20) blend pellets; 0.574 – during combustion of buckwheat hull; 0.59 – during combustion of corn stalk pellets; 0.87 – lignin and mazut (ratio 80:20) blend pellets; point 1.235 – during combustion of corn flour pellets; point 1.87 – sludge and sawdust (ratio 25:75) blend pellets; point 2.03 – during combustion of dry pig manure [9]; point 2.9 – sludge and sawdust (ratio 50:50) blend pellets; point 3.07 – poultry litter and manure blend; 3.9 – chipped wood (particle board) waste; point 4.09 – burning fruit/vegetable waste [9]; point 4.49 – sludge pellets after digestion tank; point 5.27 – stabilized sewage sludge pellets; point 7.5 – burning meet and bone meal [6]

Fig. 11 shows dependence of fuel bound nitrogen conversion on nitrogen content in the fuel.

Having analysed the results obtained, we can see that the higher nitrogen content in the combusted fuel is, the smaller part of this nitrogen migrates to nitrogen oxides. E. g.: when nitrogen content in the fuel is approximately 2%, approximately 8% of nitrogen migrates to NOx. Where as, with 0.2 percent of nitrogen content in the combusted fuel, approximately 30% of nitrogen migrates to NOx. If nitrogen content in the fuel is low, i. e., < 0.1%, then degree of conversion is approaching 90%.

The results of research have shown that fuel bound nitrogen conversion into NOx may be generalized by the equation:

$$K_N = 10.555N_F^{-0.582}. \quad (6)$$

During the research it has been established that expression of the factor of conversion of biofuel bound nitrogen into NOx (4) is similar to that when other type fuels are combusted – liquid fuel, gas and waste [6]

$$K_N = 10.095N_F^{-0.9109}.$$

In order to find out what influences conversion of nitrogen into nitrogen oxides, some tests have been carried out, during which some types of additives have been added to the fuel – wood pellets, artificial additives containing nitrogen. 4 types containing different content of nitrogen have been prepared – wood pellets spryed with such a content of carbamide that the nitrogen content in the pellets has made up: 0.3%; 0.5%; 1.0% and 2.5%. Wood pellets have been chosen as low nitrogen content fuel, featuring good quality of burning. Having sprayed the wood pellets with carbamide solution evenly, they have been dried for 7 periods of 24-hours at 20°C temperature, periodically stirring.

For natural wood pellets with  $N_F = 0.13\%$ , combustion modes, air quantity, fuel supply velocity have been determined that later would have been maintained the same when burning wood pellets with different nitrogen contents. The greatest measured NOx value in the pellets without  $N$  additives has made approximately 170 mg/m<sup>3</sup>. Combustion of wood pellets with nitrogen additive ( $N_F = 0.3\%$ ) has taken place in a very similar way as in the case of pure wood pellets, while nitrogen oxide concentrations have increased up to 400-550 mg/m<sup>3</sup>.

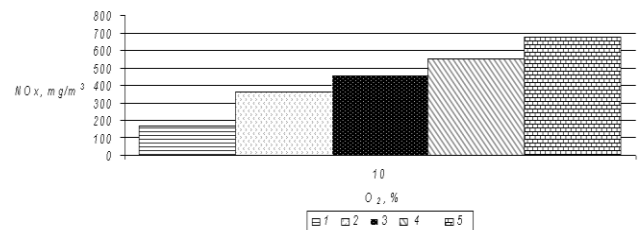


Fig. 12 NOx dependence from oxygen during combustion wood pellets with karbamide additives: 1 – wood pellets when  $N_F = 0.13\%$ ; 2 –  $N_F = 0.3\%$ ; 3 –  $N_F = 0.5\%$ ; 4 –  $N_F = 1.0\%$ ; 5 –  $N_F = 2.5\%$

When burning wood pellets with  $N_F = 0.5\%$ , the combustion has become more complicated, high CO concentrations have been detected in combustion products. With nitrogen content of 1.0%, NOx concentration has

been three times greater than in natural wood pellets, while CO concentration has been similar as in the case of wood pellets with 0.5% nitrogen. When burning pellets with even higher content of nitrogen (2.5%), the concentrations of nitrogen oxides and carbon monoxide in combustion products have increased even more. The results of research are provided in Fig. 12.

It has been established that, increasing the nitrogen content in the fuel artificially, NOx concentration value may be predicted, e.g., increasing nitrogen content in the fuel twice (e. g., from 0.5% to 1%), the NOx concentration in combustion products increases up to 1.3 times.

In order to find out whether a nitrogen source influences the conversion, i.e., a natural source (e. g., biofuel) or artificial additives, two diagrams have been composed distributing the results of research by nitrogen source (Fig. 13).

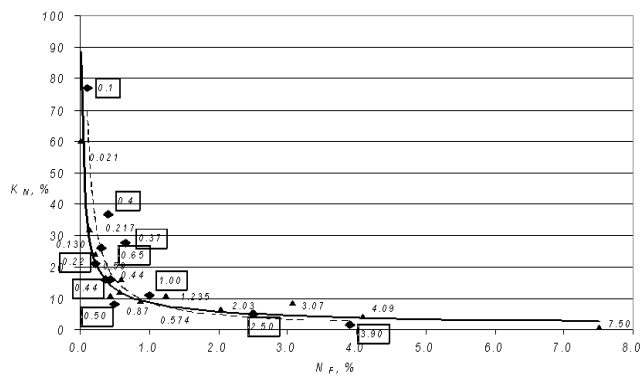


Fig. 13 Dependence of the factor of nitrogen conversion into NOx on nitrogen content in the fuel: a solid line – burning the fuel with organically bound nitrogen, a dotted line – with artificial nitrogen additives. Point values the same as in Fig. 11

Analysis of the research has shown that conversion of nitrogen from fuel with organically bound nitrogen into NOx approximately may be generalized by the equation:

$$K_N = 8.5917 N_F^{-0.603} \quad (7)$$

While conversion of nitrogen from fuel with artificial nitrogen additives into NOx approximately may be generalized by the equation:

$$K_N = 8.552 N_F^{-0.909} \quad (8)$$

It can be seen that expression of the factor of conversion of fuel bound nitrogen into NOx when burning fuel with artificial nitrogen additives is extremely similar to the factor of conversion when fuel with organically bound nitrogen is burning.

On the basis of results of experimental investigations, a method of calculation of NOx concentration, formed from the fuel bound nitrogen, has been prepared.

Having applied the above formulae (3), (4), (5) and (6), NOx concentration in combustion products from the fuel bound nitrogen, at excess air coefficient, corresponding to O<sub>2</sub> = 6%, may be calculated as follows:

$$C_{NOx} = \frac{3468.373 N_F^{0.418}}{0.000358 Q_z + 0.985} \quad (9)$$

The factor of conversion of the fuel bound nitrogen into NOx depends on nitrogen content in the fuel – if it increases, the conversion factor decreases. It has been established that the expression of the factor of conversion of biofuel bound nitrogen into NOx is similar to the one when burning other types of fuel – liquid fuel, gas and waste. Artificial additives to the fuel have a similar value of conversion into NOx as in the case of burning the fuel with organically bound nitrogen content. A method of calculation of NOx concentration, formed from the fuel bound nitrogen, has been prepared.

#### 3.4. Influence of oxygen concentration on fuelbound nitrogen conversion into NOx

The research has shown that NOx formation depends on oxygen concentration in the combustion chamber. When O<sub>2</sub> increases, concentration of nitrogen oxides increases as well.

Fig. 14 provides dependencies of NOx on oxygen concentrations when burning wood pellets with different content of nitrogen. By cross-sections in the points when O<sub>2</sub> is equal 7; 9; 10.5; 12%, we can see that the higher content of oxygen is in the stoker, the higher content of nitrogen migrates to NOx. For instance: when fuel bound nitrogen content is increased twice (from 0.5% to 1%), with oxygen 12% in the stoker, the increase in NOx reaches 145 mg/m<sup>3</sup>, i. e., by 26%.

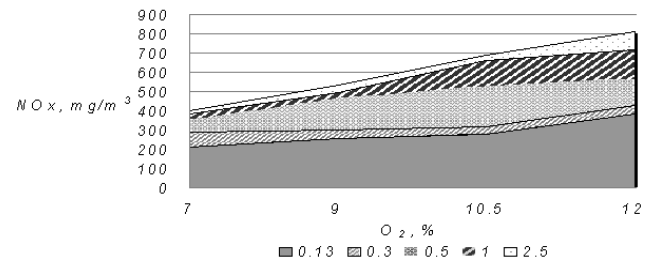


Fig. 14 NOx dependence on oxygen: 0.13 – wood pellets where N<sub>F</sub> = 0.13%; 0.3 – wood pellets with karbamide when N<sub>F</sub> = 0.3%; 0.5 – N<sub>F</sub> = 0.5%; 1 – N<sub>F</sub> = 1.0%; 2.5 – N<sub>F</sub> = 2.5%

The NOx of the fuel has been established as a difference between concentrations of nitrogen oxides at different contents of nitrogen in the fuel.

It has been established that NOx formation from the fuel bound nitrogen depends not only on N content in the fuel, but also on oxygen concentration in combustion products. The higher content of nitrogen in the fuel, the stronger NOx depends on O<sub>2</sub> in combustion products.

#### 3.5. Research on reduction in n content in the fuel

It has been known [10] that after the straw has been left in the field for some time, under atmospheric factor impact, e. g., precipitation, the straw loses part of its chlorine and caustic compounds. Therefore, it has been thought to test whether there is possibility to remove a part of nitrogen compounds from chipped wood waste (furni-

ture production wood-based panels). These compounds are inserted during production process of panels spraying the chipped wood with binding matter. Since a part of these materials, e. g., carbamide, is water soluble, the samples of chipped wood have been rinsed with running water and dried to the initial moisture. The content of nitrogen in wood waste after rinsing has decreased by approximately 38% (from 3.9% to 2.4%). The fact that a part of nitrogen may be removed by means of rinsing with water shows that chemical additives existing in the panels with nitrogen compounds in part are on the surface of chipped wood pieces.

Due to N removal by means of rinsing, when burns the „rinsed out“ chipped wood waste, the NO<sub>x</sub> level has been decreased by approximately 35% (Fig. 15).

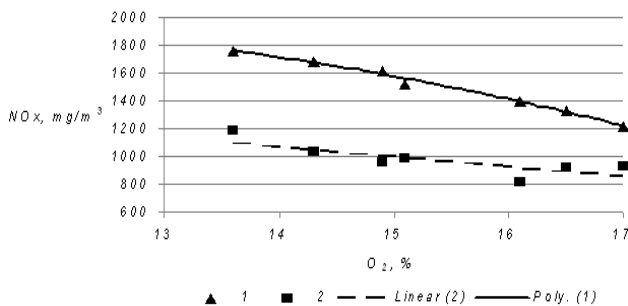


Fig. 15 Dependence of NO<sub>x</sub> on oxygen when burning: 1 – rinsed out chipped wood waste when  $N_F = 2.4\%$ ; 2 – chipped wood waste when  $N_F = 3.9\%$

As the research on biofuel thermal processing has shown (Figs. 5 and 6), when heating the fuel, the N content may be reduced in the fuel as well. During such heating – thermal processing of the fuel – a remainder is obtained, the coke. While heating chipped wood waste at 400°C temperature for 5 minutes, coke fuel has been prepared. The content of nitrogen in the coke has decreased by 9% counting from the initial nitrogen content in the chipped wood to temperature rising.

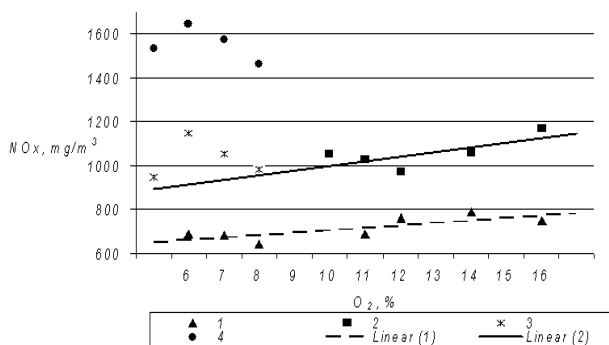


Fig. 16 NO<sub>x</sub> dependence on oxygen when burning the coke: 1 – a blend of wood waste coke and pellets (ratio 50:50); 2 – a blend of chipped wood waste and wood pellets (50:50 %); 3 – chipped wood waste coke; 4 – chipped wood waste

Coke is CO source in the layer of burning fuel and CO competes with N during oxygen binding reactions. Fig. 16 shows results, obtained when blends of coke and chipped wood waste with wood pellets are combusted. NO<sub>x</sub> concentration is lower by approximately 30% when

burning coke (i. e., wood waste after thermal processing) than burning the same fuel before thermal processing.

Due to small fraction of coal (diameter 1-2 mm), the increased air quantity and air velocity blown through the fuel layer, lifts the fuel above the air flow. On this basis, measurements of coal combustion are shown in the chart (Fig. 16) exceptionally for several modes with low O<sub>2</sub> value.

Reduction in nitrogen content in fuel by means of rinsing the fuel with water may be applied in order to decrease NO<sub>x</sub> concentrations during combustion processes.

Having conducted thermal processing on wood waste of high nitrogen content at 400°C temperature, NO<sub>x</sub> concentrations lower by approximately 30% may be achieved than those when burning the initial fuel.

#### 4. Conclusions

1. Experiments demonstrated that that the more is nitrogen content in the fuel, the less part converts into nitrogen oxides.

2. The conversion of fuel bound nitrogen to nitrogen oxides is similar to fuel of various types (solid, liquid, gaseous), irrespective of whether the fuel bound nitrogen is naturally bound or an artificially added, and may be approximately described by the following type function:

$$K_N = 10.555 N_F^{-0.582}$$

3. When raising the temperature of biofuel up to 500°C, the content up to 30% of nitrogen may be released from the fuel together with volatile substances. This explains why during initial heating of the wood and during flare-up, NO<sub>x</sub> concentrations increased markedly are observed [3]. This suggests the possibility of reducing the content of fuel bound nitrogen by means of thermal processing of the fuel.

4. Nitrogen content in the waste of chipped wood of furniture panels can be reduced by approximately 38% (from 3.9% to 2.4%) by means of rinsing the fuel with water. Due to this, NO<sub>x</sub> level can be decreased by approximately 35%.

5. In the case of high nitrogen content wood fuel, wood coke additives up to 20% reduce NO<sub>x</sub> formation by up to 44%.

6. When burning high nitrogen content fuel blends with low nitrogen content fuel, the final NO<sub>x</sub> concentration depends on what fuel of low nitrogen content has been chosen.

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R. Plečkaitienė, K. Buinevičius, E. Puida

#### KIETOSIOS FAZĖS AZOTO VIRTIMO DUJINIAIS OKSIDAIS PROCESO ANALIZĖ

#### R e z i u m ė

Darbe tiriami NO<sub>x</sub> susidarymo iš kure esančio azoto dėsningumai, deginant įvairias azoto turinčias biokuro rūšis, bei smulkintas baldų gamybos atliekas. Nustatyta, kad kuro azoto konversija į NO<sub>x</sub> mažai priklauso nuo kuro rūšies, o tai pat nuo to ar azotas kure yra natūralus ar dirbtinis priedas. Ištirta, kad kaitinant kurą iki 500°C, iki 30% azoto turinčių medžiagų išsiskiria iš kuro kartu su lakiosiomis medžiagomis. Parodyta, kad termiškai apdorojant biokurą, galima iš jo pašalinti dalį azoto. NO<sub>x</sub> susidarymą galima sumažinti, plaunant medienos plokštės atliekas vandeniu. Į azoto turintį kurą pridėjus 20% kokso NO<sub>x</sub> koncentracija sumažėja iki 44%. Daug azoto turinčio kuro deginimas kartu su mažai azoto turinčiu kuru mažina NO<sub>x</sub> susidarymą – tai priklauso ir nuo šio kuro savybių.

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#### ANALYSIS OF SOLID PHASE NITROGEN CONVERSION PROCESS TO GASEOUS OXIDES

#### S u m m a r y

In the paper, the patterns of NO<sub>x</sub> formation from fuel bound nitrogen have been analyzed when burning various types of biofuel containing nitrogen, and also chipped waste of furniture production. It has been established that fuel bound nitrogen conversion to NO<sub>x</sub> slightly depends on type of fuel and on whether the nitrogen contained in the fuel is naturally bound or is an artificial additive. It has been concluded that when heating the fuel up to 500°C, up to 30% of substances containing nitrogen releases from the fuel together with volatile substances. It has been shown that, when applying thermal processing of fuel, a part of nitrogen may be removed from the fuel. NO<sub>x</sub> formation can be reduced by rinsing the wood panels with water. 20% coke additives to fuel containing nitrogen allows reducing NO<sub>x</sub> concentration by up to 44%. Burning of high nitrogen content fuel together with low nitrogen content fuel provides ambiguous effect on NO<sub>x</sub> formation – it depends upon properties of this fuel as well.

**Keywords:** biofuel combustion, NO<sub>x</sub> concentration, conversion factor, CO.

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