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Biomass combustion research studying the impact factors of NOx formation and reduction

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Abstract. Aim of this study was to identify potential NOx reduction factors and determine impact of nitrogen quantity in the fuel, during combustion process and conversion to nitrogen oxides. Experiments were performed using moving grate biofuel boiler with two staged air inlets, which represents industrial boiler operating principles. Combustion was performed using agricultural wastes: grain middlings, buckwheat hulls, corn pellets and mixtures with wood pellets. These types of fuels in combustion process generate about two times bigger amount of nitrogen oxides than wood pellets. The result of research shows, that the amount of nitrogen in the fuel has the greatest impact for NOx generation compared to all NOx formation forms. It was found that a smaller quantity of nitrogen, has bigger impact factor, than higher quantity of nitrogen, in biomass, for NOx formation during combustion. It was noticed that during combustion process the amount of carbon monoxide is inversely proportional to NOx values. The impact factor of nitrogen conversion to NOx and CO potential of reducing NOx is presented by formula in this paper.

Key words: biomass combustion, NOx formation, CO.

INTRODUCTION

In Lithuania 60% of thermal energy is produced from renewable resource biofuel. Biofuel resources are wood, cutting wastes, straw and leaves. Growing demand of biofuel encourages to look for new renewable energy resources which could supplement the list of fuel variety.

For this purpose, the attention was paid to agricultural waste. However, agricultural waste is characterized by higher nitrogen oxide concentrations during combustion, but usage of agricultural waste is limited because of valid environmental protection standards. The first aim of this study was to identify potential NO_x reduction factors. The second aim was to determine the impact of nitrogen quantity in the fuel to the NO_x formation during combustion process.

In this work examined alternatives for biofuel include agricultural wastes: grain middlings, buckwheat hulls, corn pellets. These types of fuel during combustion process generate about two times higher amount of nitrogen oxides. The paper presents combustion techniques of the examined fuel types, experimental study results, evaluation of emission concentrations in flue gases and dependence on fuel composition. Experiments have demonstrated that the higher the content of nitrogen contained in the shape of compounds, the lower the share of this nitrogen transitioning into nitrogen oxides. The conducted studies formed the basis for the development of a formula for calculating NO_x concentrations from nitrogen contained in fuel. Main designations used in paper presented in Table 1.

Table 1. Nomenclature

Mark	Explanation	Mark	Explanation
NO_x	nitrogen oxides	W	Fuel moisture content, %
CO_2	carbon dioxide	α	excess air coefficient
K_N	nitrogen conversion factor, %	V_a^t	theoretical content of air necessary for combustion, m^3
N_K	nitrogen content in the fuel	V_g^t	theoretical flue gas volume, m^3

MATERIALS AND METHODS

Materials

The experiments were accomplished on the basic fuel – agricultural wastes (grain middlings, buckwheat hulls, corn pellets). These fuels were used as high NO_x concentration generating fuels (with high nitrogen content in mass). (Table 2) illustrates results of the used fuel nitrogen content and calorific value.

Table 2. Properties of the substances used in the research

Fuel	W, %	N_k, %	Ash, %	$Q_{w.f.l}$ kJ kg^{-1}
Grain middlings	8.0	0.59	0.38	15,617
Buckwheat hulls	8.7	0.57	0.27	15,912
Corn pellets	7.0	1.24	0.32	14,934
Wood pallets	8.7	0.13	0.17	17,100

Agricultural wastes are formed every year. During the annually cutting, cereal processing and other technological process of agricultural products, some of it remains as a waste. Consequently, agriculture companies show and interest to use these wastes to meet their own energy needs.

In Lithuania, a large amount of such wastes are created and cannot be used as a fuel due to large quantities of nitrogen oxides generated during combustion process. However, in case of a successful reduction of the nitrogen contents conversion to nitrogen oxides, type of such biomass could be used in energy production. Moreover, it could reduce amounts of waste disposed in landfills and decrease the amount of wood used in energy production.

Fuels used for research were not additionally treated just dried up. All type of fuels are small fraction 2–5 mm size middlings, hulls and small pallets (6 mm diameter). Fuel is supplied to the combustion chamber by the mechanical feeder. Fuel in combustion zone is blown by primary air, which does not take away unburned particles to the chamber and combustion process going smoothly.

Methods

Experiments were carried out in the Combustion research laboratory of Kaunas University of Technology, which has an installed pellets-fired industrial boiler model and all other system elements shown in (Fig. 1).

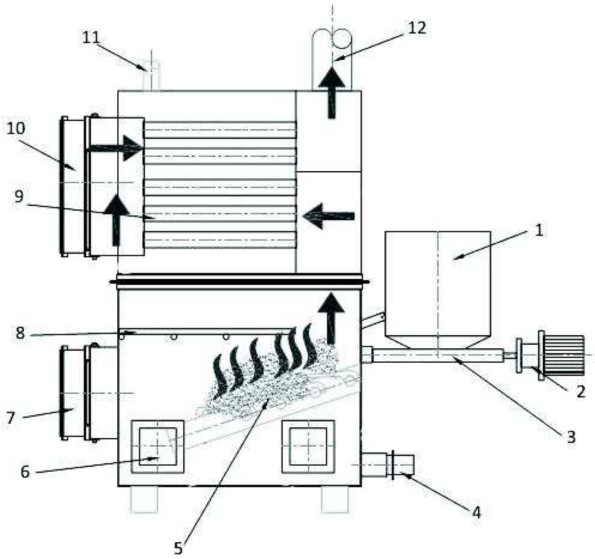

Figure 1. Laboratory combustion research stand: 1 – Fuel container; 2 – Electric motor; 3 – Mechanical feeder; 4 – Primary air inlet; 5 – Moving grate; 6 – Ash hopper; 7 – Inspection window; 8 – Secondary air inlet; 9 – Fire tube boiler; 10 – Inspection door; 11 – Heated water outlet; 12 – Chimney.

The main component of the stand is furnace, which has systems for fuel and air feeding. Furnace and heat exchange surfaces, are the main two components of the water boiler. The operating load of the boiler can vary from 25 to 40 kW Draft fan with a frequency converter assists to emit flue gases to the chimney to keep stable pressure in the combustion chamber.

Branch pipe for flue gas analysis probe is installed in the flue gas pipe in order to be able to make flue gas analysis and temperature measurements. About 20 °C temperature air for combustion is fed from the surrounding environment. Boiler water temperature is maintained to stay in between 65 °C and 70 °C. Cooling system consists of a heater block with a cooling fan which is constantly fed with pumping water in order to ensure uninterruptible heat transfer.

There are two parameters that control a combustion of all fuel types. First is fuel feeding rate and second is the amount of air that is supplied to the combustion chamber. Flue gas analyser measures generated pollutant concentrations. This analyser measures temperatures and concentrations of nitrogen oxides, nitrogen monoxide, oxygen and carbon monoxide in the exhaust gases.

All the measured made from the dry gasses and concentration of CO and NOx emissions normalized to 6% of O_2.

Frequency converter, which is mounted on the side of the furnace, is used to determine the constant rate of fuel feeding and according to this value, it also regulates the amount of air for combustion. Tank for ash is at the bottom of the grate.

The fuel is burnt so that the temperature in the combustion zone would not exceed 1,200 °C; burning at such temperature mode would allow examining solely the generation of 'fuel NOx', because this temperature is insufficient for the formation of 'thermal NOx' (Hodžic et al., 2016). At this temperature range, its share in the NOx content is so small, that it has no practical value (Javed et al., 2007).

In order to examine biomass samples in a larger total nitrogen spectrum, blends of agriculture waste and wood pellets were prepared. Wood pellets used in the preparation of blends had small nitrogen content up to 0,13 percent, while lower calorific value of fuel was 17,1 MJ kg^{-1}. Blends mechanically were mixed by mass proportions shown in (Table 3).

Table 3. Properties of the fuel blends

Fuel blends	W, %	N_k, %	Ash, %	$Q_{w.f.l}$ kJ kg^{-1}
Blend of grain middlings	8,35	0.36	0.28	16,359
Blend of buckwheat hulls	8.7	0.35	0.22	16,506
Blend of corn pellets	7.85	0.69	0.25	16,017

All the blends made with mass proportion in 50 percent wood pallets and 50 percent original fuel.

COMBUSTION RESEARCH

Experimental fuel combustion research was conducted with the aim to examine the amount of pollutants contained in flue gases.

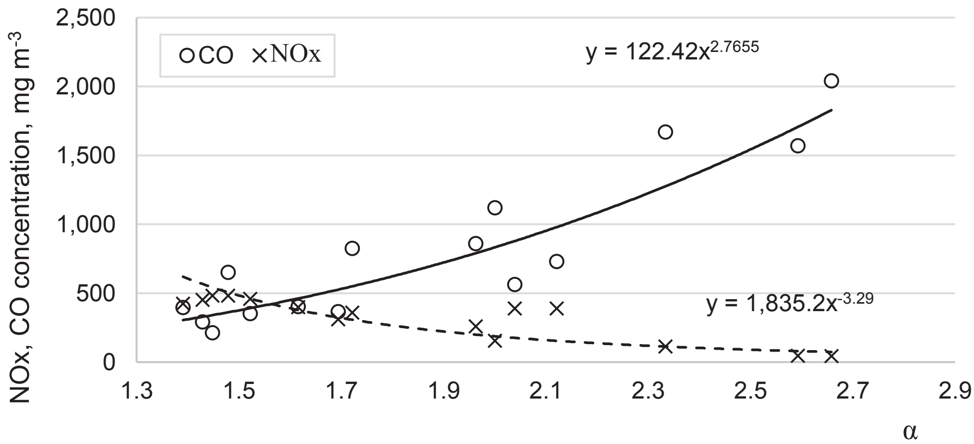

Figure 2. NOx and CO emissions values dependent on excess air ratio (α). Fuel – grain middlings.

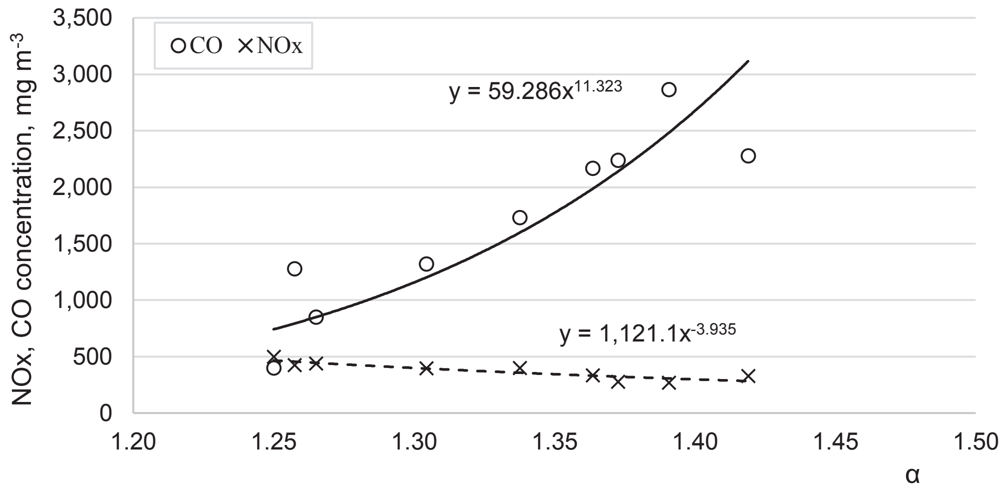

Figure 3. NO_X and CO emissions values dependent on excess air ratio (α). Fuel – buckwheat hulls.

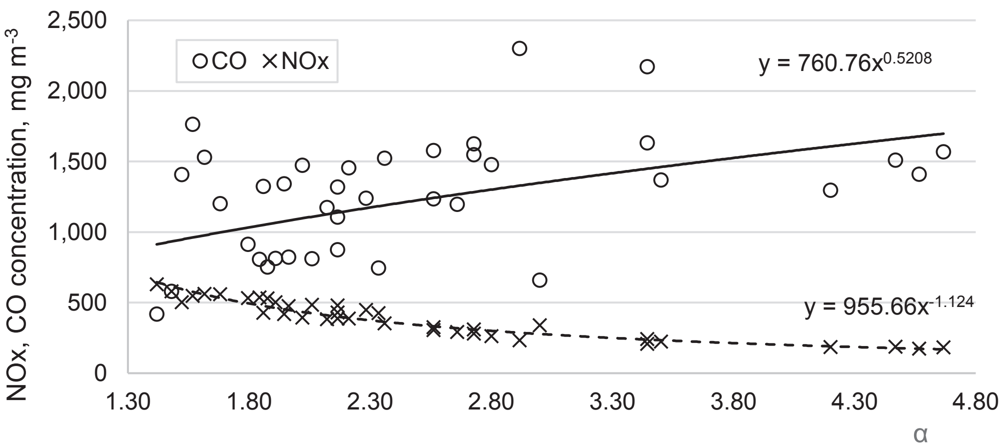

Figure 4. NOx and CO emissions values dependent on excess air ratio (α). Fuel – Corn pellets.

Summary research graphs of the examined waste reveal that the corn pallets with highest nitrogen content generates large amounts of nitrogen oxides of up to 700 mg m^{-3}. Burning other agricultural waste with two times smaller nitrogen content in fuel NO_X concentration reaches 500 mg m^{-3}. This shows that different N content in the substances turns to nitrogen oxides unevenly, and the lower the nitrogen content in the substance, the greater part of it converts to nitrogen oxides.

The highest recorded CO concentrations ranged from 2,100 mg m^{-3} when burning grain middlings and to 2,700 mg m^{-3} when burning buckwheat hulls.

A trend was observed that with an increasing excess air in the furnace above 1.4, NOx concentration in flue gases decreased (Carroll et al., 2015). It has already been known from other sources (Li et al., 2012) and observed in the conducted experimental research, increasing CO concentration in flue gases has a decreasing effect on NOx generation in flue gases.

Thus in order to determine the dependence of the formation of nitrogen oxides on the content of nitrogen in substances, calculations of the values of the conversion coefficient were conducted. The K_N coefficient of nitrogen conversion to NO_X is calculated as the share of nitrogen contained in fuel having transitioned to NO_X, according to the equation (Buinevičius et al., 2011):

$$K_N = \frac{\left(V_g^t + (\alpha - 1)V_a^t\right) \cdot C_{NO_X}}{328.6 \cdot N_K} \quad (1)$$

where: α – excess air coefficient in flue gases; C_{NO_X} – nitrogen oxides concentration in flue gases, mg m^{-3}; 328.6 – recalculation coefficient;

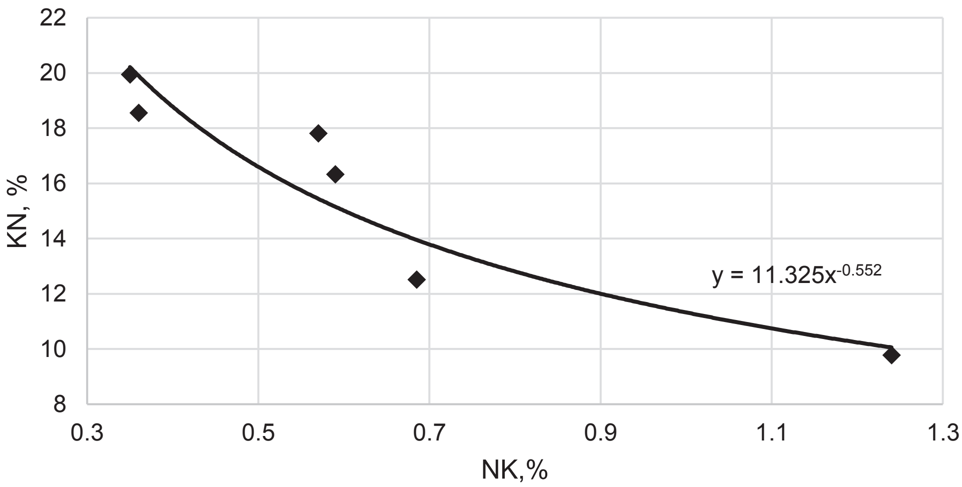

Figure 3. The total approximating nitrogen curve of nitrogen conversion from fuel.

In summary of all the examined materials with higher nitrogen content, a summary graph is drawn up (Fig. 3), with a derived function describing a conversion factor of all examined fuel samples:

$$K_N = 11.325 \cdot N_K^{-0,552} \quad (2)$$

This function may be used to calculate the nitrogen oxides conversion factor in agricultural waste where N amount in mass is less than 1.3%.

Calculation of NO_X concentrations

In order to evaluate the NO_X generation dependence on the nitrogen conversion factor described in formula (3), a formula was drawn up allowing calculating NOx concentration (mg m^{-3}) forming during the combustion process:

$$C_{NO_X} = \frac{328.6 \cdot K_N \cdot N_K}{V_a^t \cdot (\alpha - 1) + V_g^t} \quad (3)$$

The calculation on NO_X concentration by formula (3) gives deviation when in flue gas appears higher amount of carbon monoxide. In order to avoid this error CO influence to NO_X is calculated. The graphs below show the CO influence to NO_X correction.

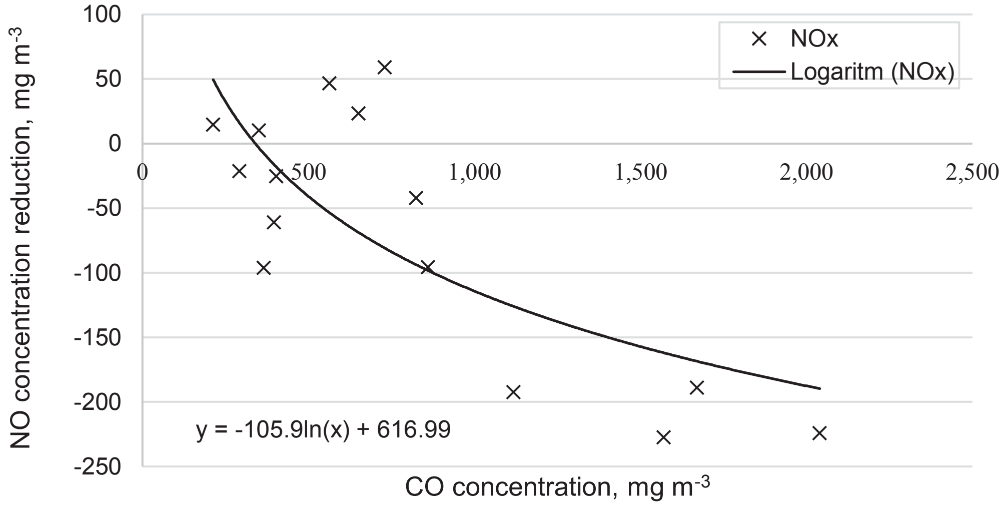

Figure 5. The CO influence to NO_X concentration. Burning grain middlings.

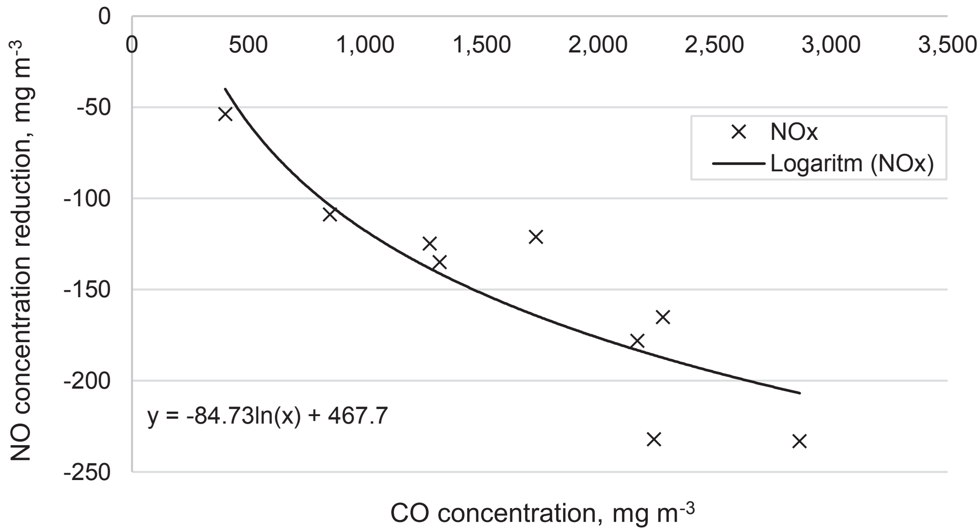

Figure 6. The CO influence to NO_X concentration. Burning grain middlings.

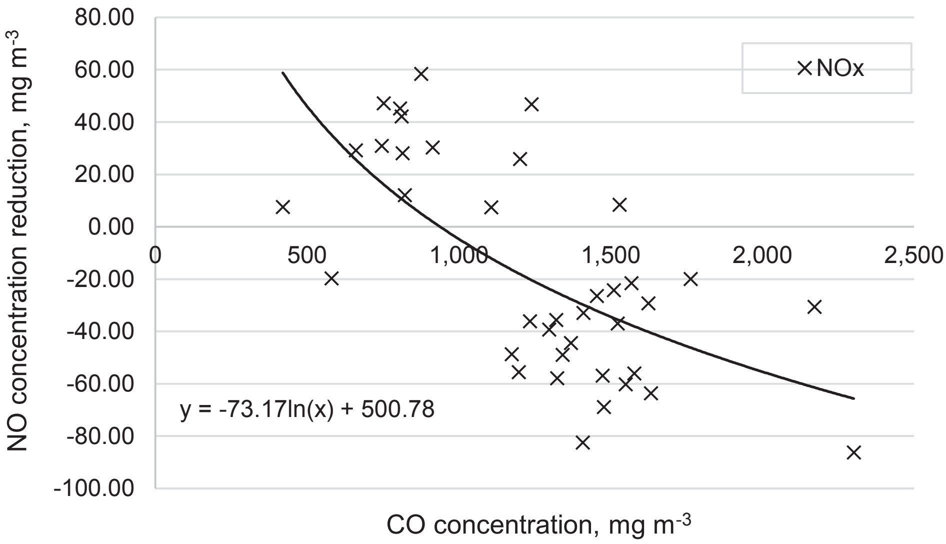

Figure 7. The CO influence to NO_X concentration. Burning corn pallets.

According to (Fig. 5–7), the highest NO_x concentration reduction was measured while burning buckwheat hulls up to 250 mg m^{-3}. It was determined that the CO concentration greater than 500 mg m^{-3} has a noticeable influence to NO_X concentration reduction.

To specify the formula (3) and additionally evaluate the carbon monoxide impact factor for agricultural wastes, approximates formula was derived:

$$K_{CO} = -87.93 ln\,(C_{CO}) \; + 528.49 \qquad (4)$$

where: C_{CO} – carbon monoxide concentration in flue gases, mg m^{-3}

Summing up the formulas (3 and 4) is written new formula:

$$C_{NO_X} = \frac{328.6 \cdot K_N \cdot N_K}{V_a^t \cdot (\alpha - 1) + V_g^t} - 87.93 ln\,(C_{CO}) \; + 528.49 \qquad (5)$$

The obtained result reveals that NO_X concentration in flue gases depends on the volume of flue gases. It has a direct dependence on lower calorific value of fuel (Plečkaitienė & Buinevičius, 2011) and values of excess air coefficient (Kuang et al., 2014), nitrogen content in fuel (Wang et al., 2012) and the compiled nitrogen conversion coefficient, which is expressed via the recalculation coefficient and the CO concentration in exhaust gases.

CONCLUSIONS

Noticed that different N content in the substances turns to nitrogen oxides unevenly, and the lower the nitrogen content in the substance, the greater part of it converts to nitrogen oxides. Confirmed in experimental research, that increasing CO concentration in flue gases has a decreasing effect on NO_X generation in flue gases.

To additionally evaluate the carbon monoxide impact factor for agricultural wastes, approximates formula was derived and summed up the formulas for NO_X concentration calculation. The new formula assess hat NO_X concentration in flue gases depends on the volume of flue gases, which has a direct dependence on lower calorific value of fuel and values of excess air coefficient, nitrogen content in fuel and the compiled nitrogen conversion coefficient, which is expressed via the recalculation coefficient and the CO concentration in exhaust gases.

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