

## Article

# Extensive Operating Experiments on the Conversion of Fuel-Bound Nitrogen into Nitrogen Oxides in the Combustion of Wood Fuel

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**Abstract:** This paper presents a wide, targeted, operational experiment on the conversion of fuel-bound nitrogen to nitrogen oxides. The experiment was implemented by studying the production of energy in 16-grate boilers. The conversion factor was determined based on the nitrogen content in individual types of dendromass and on nitrogen oxide emissions in flue gases. In measuring emissions, 103 average values for the concentration of nitrous oxide were found. Every average value was set using three consecutive half-hour emission measurements. The specific thermal output of the boilers was 300 to 2500 kW. The nitrogen content in the deliberately selected dendromass was within a wide interval of  $N^{daf}$  values between 0.04% and 1.26%. The dependence of the conversion factor,  $X_{NO_x}$ , upon the content of fuel-bound nitrogen is very accurately expressed by the power function.

**Keywords:** combustion; dendromass; conversion factor; fuel-bound nitrogen; nitrogen oxides

## 1. Introduction

Chemically bound nitrogen in organic matter is converted during combustion into a variety of inorganic forms, mainly molecular nitrogen ( $N_2$ ) and the nitrogen oxides, NO and  $NO_2$ . The proportion of nitrogen oxides ( $NO_x$ ) formed is not clearly predictable because it depends on numerous factors such as the proportion of nitrogen in organic matter, combustion technology, and the specific conditions in the combustion chamber.

As the amount of nitrogen oxides formed during the combustion of fossil fuels and biofuels is very important in terms of air pollution, this issue has been given due attention [1]. In terms of air pollution, it is important to design and operate combustion equipment so that it produces the lowest possible volume of nitrogen oxides. Large combustion plants, designed and operated according to the best available techniques (BAT), operate using effective techniques and measures for the removal of pollutants. The BAT recommendations for the reduction of  $NO_x$  emissions and the associated emission levels for various fuels are summarized in a reference document that covers combustion installations with a rated thermal input exceeding 50 MW [2].

The production of biomass-based energy mainly uses grate furnaces with a thermal input of less than 50 MW. The level of development of these medium and small combustion plants, therefore, is not explicitly defined. There is marked variability in the chemical composition of the biomass, which is also reflected in the marked dispersion of concentrations of nitrogen oxides in flue gases from biomass combustion. Because the current emissions limits for  $NO_x$  from combusting biomass are not

sufficiently strict, researchers have not yet dealt with what minimal values of concentration could be achieved in practice.

Experimental research and modelling of the fuel combustion processes can be used to clarify the formation of nitrogen oxides [3,4]. The combustion of forest biomass (dendromass) should be regulated so that nitrogen oxides emissions are minimized. Pilot experiments and measurements of nitrogen oxide emissions in specific combustion devices have also aimed at minimizing emissions. Statistical evaluation of older available data on types of combusted wood fuel, combustion plants, and pollutant concentrations using factor analysis have shown that combustion technique has a decisive influence on basic pollutant emissions except for  $\text{NO}_x$  [5]. Nussbaumer (1991) [6] measured conversion factors for  $\text{NO}_x/\text{Fuel-N}$  from 8.4% to 67.3% in laboratory boilers. Stubenberger et al. (2007) [7] investigated the differences of various solid biomass fuels in releasing N and forming N flue gas species using a lab-scale reactor for biomass fuel and one pilot-scale plant. The lab-scale reactor used for the experimental work was a discontinuously operated cylindrical fixed bed reactor, from which it was not possible to get results for the conversion of fuel N into  $\text{NO}_x$ . In the pilot-scale plant with a reciprocating horizontal grate (the nominal boiler capacity being 440 kWth) and primary and secondary combustion zones, the following values of conversion were measured: –88% for sawdust (fuel concentration N = 0.06%), 22% for bark (fuel concentration N = 0.27%) and 5% for MDF board (fuel concentration N = 6.87%). Pleckaitine and Buinevicius [8] used laboratory experiments to define the dependence of the conversion coefficient on the nitrogen content in fuel. A prototype of a biomass grate-fired unit with a nominal useful output of 250 kWth was used by Díaz-Ramírez et al. (2014) [9] to evaluate the applicability of the three pelletized energy crops. They found conversion factors of  $\text{NO}_x/\text{Fuel-N}$  from  $14.5\% \pm 0.8\%$  to  $71.4\% \pm 1.9\%$ .

To date, studies have consisted of model experiments under laboratory conditions or measurements of the conversion of fuel-bound nitrogen in individual boilers under varying conditions. The actual value of the results of these model experiments is limited and difficult to generalize. Dzurenda et al. (2015) [10] carried out an extensive study combusting spruce wood and monitoring the conversion of fuel-bound nitrogen into nitrogen oxides under real conditions in 16 grate boilers. Their emission measurements were mostly carried out in modern boilers with grate furnaces developed in the early 21st century, for which the conversion factor was  $65.4\% \pm 8.3\%$ .

The existing research therefore has not established representative conversion factor values for the conversion of fuel-bound nitrogen into nitrogen oxides. Representative values must be gathered from a wide spectrum of emission measurements based on operationally combusting dendromass with varying fuel-bound nitrogen contents. This is the aim of this paper. No similar extensive experiment to find the representative values of conversion factor fuel-bound nitrogen into nitrogen oxides has been carried out so far. Establishing representative conversion factors for converting fuel-bound nitrogen into nitrogen oxides can be used to estimate the lowest achievable concentrations of nitrogen oxides.

The dendromass used for our study was debarked deciduous and coniferous trees, bark, and energy chips from plantation-grown, fast-growing tree species. The functional dependency for dendromass with nitrogen in the dry and ash free matter ( $N^{\text{daf}}$ ) was determined to be in the range of 0.04%–1.26%. This dependency was based on extensive targeted operating experiments on energy generation in grate furnace boilers with a rated thermal input of 300–2500 kW.

## 2. Materials and Methods

### 2.1. Dendromass for Combustion Tests

The following was specially prepared for the combustion test:

- Moist wood chips and sawdust were prepared from spruce (*Picea exelsa* (L.)), Scots pine (*Pinus sylvestris* (L.)), common beech (*Fagus sylvatica* (L.)), and black locust (*Robinia pseudoacacia*). Wood chips and sawdust were produced from debarked wood from forest stands that had not been chemically treated during their cultivation.

- Crushed tree bark was obtained from the debarking of spruce (*Picea excelsa* (L.)) and English oak (*Quercus robur* (L.)).
- Moist wood chips were also produced from plantation-grown, fast-growing tree species with a short rotation coppice (SRC), including common osier (*Salix viminalis*) and black locust (*Robinia pseudoacacia*); the forest stands had not been treated by any chemical means.

For the collected representative samples of dendromass chips from individual operators, humidity was determined and elementary element analysis was conducted to quantify the C, H, and N contents (though in this paper we indicate only the content of N). In order to determine the nitrogen content in dry ash and ash-free matter ( $N^{daf}$ ), we also determined the ash content of the investigated dendromass. Differences in ash content between different types of dendromass were relatively small and did not affect concentration of  $NO_x$  emissions. For this reason, we have not indicated the value of ash content. For SRC species, the proportion of bark in the chips was determined as well as wood and bark moisture content, after which an elemental analysis of wood and bark was performed. At all operators we studied, the fuel was prepared and stored in the same way in the winter months, so the differences in moisture between the individual plants were small. Given the non-significant differences in the nitrogen content of the same types of samples among the operators, calculations were performed using only the average values.

## 2.2. Industrial Wood Boiler

Emission measurements were carried out on modern, fully automated boilers intended for biofuel combustion (Table 1). The furnaces in Multimiser boilers (Danstoker, Plc., Herning, Denmark) were designed to burn fuel at a low heat load, thereby creating conditions for optimum biofuel combustion and low nitrogen oxide emissions. Similarly, Firematic FR 300 boilers (Herz Energietechnik GmbH, Pinkafeld, Austria) ensure an optimum furnace temperature for biomass combustion by a water-cooled grate and an electronically-controlled BioControl 3000 (Herz Armaturen GmbH Sebersdorf, Austria) for fuel combustion. Other combustion plants use the hot water boiler TPS (ELBH, Ltd., Týn nad Vltavou, Czech Republic).

**Table 1.** Types of boilers and their boiler input.

Boiler Type	Number of Boilers (pcs)	Boiler Input (kW)
MULTIMISER 20	1	2200
MULTIMISER 19	1	1750
MULTIMISER 16	1	880
MULTIMISER 15	4	725
MULTIMISER 14	1	560
MULTIMISER 13	2	425
MULTIMISER 12	1	350
FIREMATIC FR 300	3	300
TPS 100	1	1163
TPS 35	1	440

## 2.3. Modelling the Conversion of Fuel-Bound Nitrogen into Nitrogen Oxides

The conversion factor for converting fuel-bound nitrogen into emissions of nitrogen oxides  $X_{NO_x}$  is defined as the percentage ratio of the concentration of nitrogen oxide emissions in the combustion gases, as determined by emission measurements, to the theoretical concentration of nitrogen oxides calculated by Equation (1). Emissions from wood combustion are converted to 11% oxygen content in the resulting dry combustion gases; therefore, the calculated concentration is converted to the same oxygen content in dry combustion gases.

$$X_{NO_x} = \frac{C_{NO_x}}{C_{maxNO_x}} \times 100 \quad (1)$$

where  $X_{\text{NO}_x}$  (%) is the coefficient of the conversion of fuel-bound nitrogen into emissions of nitrogen oxides;  $C_{\text{NO}_x}$  (mg/m<sup>3</sup>) is the concentration of NO<sub>x</sub> in the combustion gases, determined by emission measurements; and  $C_{\text{maxNO}_x}$  (mg/m<sup>3</sup>) is the theoretical (maximum) concentration of NO<sub>x</sub> in the combustion gases, formed by the complete oxidation of nitrogen present in the fuel, determined by a technical calculation.

The maximum concentration of NO<sub>x</sub> in the combustion gases  $C_{\text{maxNO}_x}$  (kg/m<sup>3</sup>) that would be formed by 100% conversion is described by the equation Equations (2)–(4):

$$C_{\text{maxNO}_x} = \frac{\max m_{\text{NO}_x}}{\min V_c} \quad (2)$$

$$C_{\text{maxNO}_x} = \frac{\frac{M_{\text{NO}_2}}{A_N} \times N^{\text{daf}}}{\frac{V_m}{A_C} \times C^{\text{daf}} + X_{\text{N}_2} \times V_{\text{air}} + (\lambda - 1) \times V_{\text{air}}} \quad (3)$$

$$C_{\text{maxNO}_x} = \frac{3.2857 \times N^{\text{daf}}}{1.8555 \times C^{\text{daf}} + 0.7905 \times V_{\text{air}} + (\lambda - 1) \times V_{\text{air}}} \quad (4)$$

where  $\max m_{\text{NO}_x}$  (kg) is the maximum mass of nitrogen oxides formed by the combustion of 1 kg of combustible matter;  $\min V_c$  (m<sup>3</sup>) is the minimum volume of combustion gases formed by the combustion of 1 kg of combustible matter according to a stoichiometric calculation;  $M_{\text{NO}_2}$  (g/mol) is the molar mass;  $A_N$  (g/mol) is the standard atomic weight of nitrogen;  $A_C$  (g/mol) is the standard atomic weight of carbon;  $V_m$  (dm<sup>3</sup>/mol) is the molar volume of an ideal gas at 1 atmosphere of pressure is 22.414 dm<sup>3</sup>/mol at 0 °C;  $X_{\text{N}_2}$  (–) is the proportion of nitrogen in the air;  $N^{\text{daf}}$  (kg/kg) is the nitrogen content in the combustible matter;  $C^{\text{daf}}$  (kg/kg) is the carbon content in the combustible matter;  $V_{\text{air}}$  (m<sup>3</sup>/kg) is the stoichiometric amount of combustion air needed for the combustion of 1 kg of combustible matter; and  $\lambda$  (–) is the excess combustion air.

## 2.4. Analytical and Measurement Methods

### 2.4.1. Determination of Water in Dendromass

From the samples collected, three analytical samples were used to determine the water content according to EN 14774-2 [11], i.e., a gravimetric method with drying at atmospheric pressure and a temperature of 105 ± 2 °C.

### 2.4.2. Determination of C, H, and N in Dendromass

The carbon, hydrogen, and nitrogen contents in the dendromass were determined using an NCS-FLASH EA 1112 analyzer (Thermo Finnigan, San Jose, CA, USA) (though in this paper we indicate only the content of N). The nitrogen contents of SRC were determined by a calculation based on the proportion of bark in the wood chips and on the measured values of nitrogen in the wood and bark using Equation (5):

$$N_{\text{SRC}}^{\text{daf}} = \left[ \frac{100 - X_B}{100} \right] \times N_W^{\text{daf}} + \frac{X_B}{100} \times N_B^{\text{daf}} \quad (5)$$

where  $N_{\text{SRC}}^{\text{daf}}$  (%) is the nitrogen content in combustible matter of SRC;  $N_W^{\text{daf}}$  (%) is the nitrogen content in combustible matter of wood;  $N_B^{\text{daf}}$  (%) is the nitrogen content in combustible matter of bark; and  $X_B$  (%) is the proportion of bark in chips.

### 2.4.3. Emissions Measurement

For this study, we measured emissions from 16 different grate-hearth boilers. In the studied boilers, different types of woody biomass were burnt: *Picea excelsa* L.—wood, bark; *Pinus sylvestris* L.—wood; *Quercus robur* L.—wood, bark; *Fagus sylvatica* L.—wood; *Salix viminalis*—component wood;

*Salix viminalis*—component bark; *Robinia pseudoacacia*—component wood; *Robinia pseudoacacia*—component bark. Under stable operation of the boilers with minimum output power of 90%, the emission values of NO<sub>x</sub>, CO, SO<sub>2</sub>, and O<sub>2</sub> were determined according to ISO 10849 [12], EN 15058 [13], ISO 7935 [14], and EN 14789 [15], respectively. In measuring emissions, 103 average values for concentration of nitrogen oxide were found. Every average value was determined using three consecutive half-hour emission measurements.

Emission gas concentrations were measured using an ENDA 6000 portable gas analyzer (Horiba, Kyoto, Japan). The measurement methods used were NDIR for NO<sub>x</sub>, CO, and paramagnetism for oxygen. The inert sampling probe and sampling tube were heated to 200 °C. Calibration gases (NO<sub>x</sub> in N<sub>2</sub>) for the gas analyzers were supplied by Linde Gas (Bratislava, Slovakia) and used at a concentration of 100–250 ppm.

To determine the conversion factor, only the concentrations of nitrogen oxides are important and indicated. To demonstrate the quality of combustion, the concentrations of carbon monoxide are indicated. The relative standard uncertainty of the measurement of nitrogen oxides mass in the combustion gases during the emission measurements with the ENDA 6000 analyzer was  $u_{\text{NO}_x} = 5\%$ . The pollutant concentrations measurements correlate to dry gas at 11% oxygen content in the combustion gases.

### 3. Results

Dendromass for the operating combustion experiments was represented by specially prepared samples of debarked wood from coniferous and deciduous trees, crushed bark, and wood chips from the dendromass of forests stands with plantation-grown, fast-growing tree species. Hence, fuel dendromass was prepared with a wide range of nitrogen content, from 0.04% to 1.26% (dry ash free). The theoretical values of maximum concentrations of NO<sub>x</sub> in the combustion gases (according to a stoichiometric calculation) ranged from 136 mg/m<sub>n</sub><sup>3</sup> to 4139 mg/m<sub>n</sub><sup>3</sup> (converted to 11% O<sub>2</sub>).

The average values of nitrogen content in the dendromass, including the values of the uncertainty of determining the average value, and the calculated maximum values of the concentration of nitrogen oxides (NO<sub>x</sub>) in dry combustion gases (converted to 11% O<sub>2</sub> in the combustion gases) according to Equation (4) are given in Table 2.

**Table 2.** Average nitrogen content in the combustible matter of dendromass and theoretical values of maximum concentrations of NO<sub>x</sub> in the combustion gases (converted to 11% O<sub>2</sub>).

Dendromass	N <sup>daf</sup> (%)	C <sub>maxNOx</sub> (mg/m <sub>n</sub> <sup>3</sup> )	
<i>Picea excelsa</i> L.—wood	0.04 ± 0.002	136	
<i>Pinus sylvestris</i> L.—wood	0.07 ± 0.002	230	
<i>Quercus robur</i> L.—wood	0.14 ± 0.01	427	
<i>Fagus sylvatica</i> L.—wood	0.15 ± 0.01	493	
Chips from SRC			
<i>Salix viminalis</i> —component wood	0.35 ± 0.02	0.58 ± 0.03 *	1906
<i>Salix viminalis</i> —component bark	1.66 ± 0.08		
<i>Robinia pseudoacacia</i> —component wood	0.58 ± 0.02	1.26 ± 0.08 *	4139
<i>Robinia pseudoacacia</i> —component bark	3.52 ± 0.08		
Crushed bark of trees			
<i>Picea excelsa</i> L.—bark	0.38 ± 0.02		1248
<i>Quercus robur</i> L.—bark	0.69 ± 0.03		2267

\* weighted average.

The moisture content of the combusted dendromass, as well as the average values and standard deviations of the concentration of nitrogen oxides (NO<sub>x</sub>) and carbon monoxide (CO) in the combustion gases, are given in Table 3.

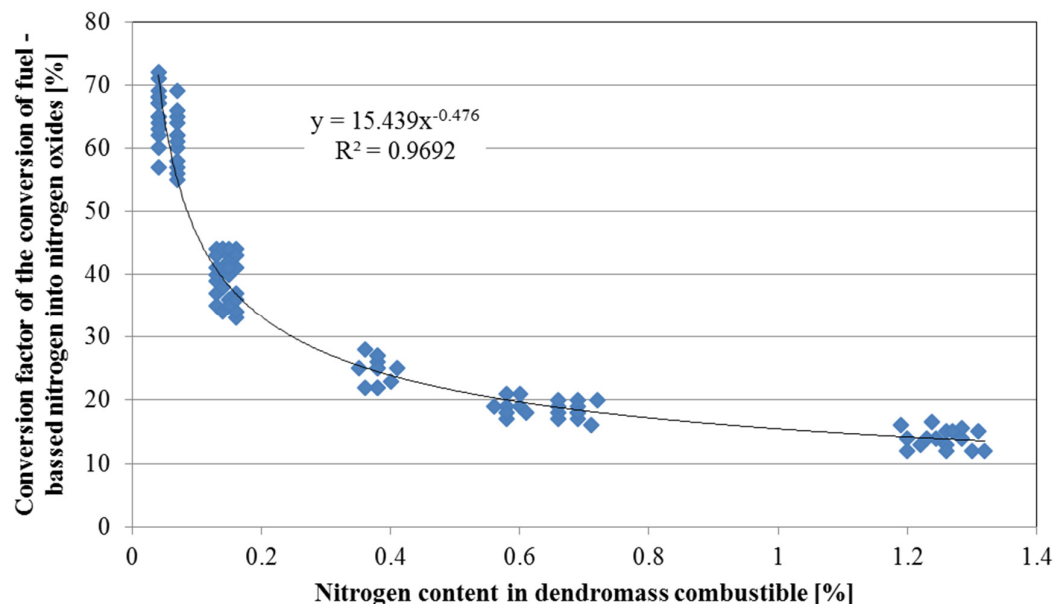
Figure 1 depicts the dependence of the conversion factor of fuel nitrogen in the emitted nitrogen oxides on the nitrogen content in the woody biomass (NO<sub>x</sub>/Fuel-N) in the combustion. The process

of combustion took place in grate-hearth boilers and the moisture content of the woody biomass was  $W^r = 33.3\%–54.1\%$ .

**Table 3.** Average concentrations of nitrogen oxides  $\text{NO}_x$  and carbon monoxide CO in dry combustion gases (converted to 11%  $\text{O}_2$ ).

Dendromass	Amount of Mean Values *	Moisture W <sup>r</sup> (%)	Average Half-Hour Emission Concentrations (mg/m <sub>n</sub> <sup>3</sup> )	
			NO <sub>x</sub>	CO
Wood chips and sawdust from debarked wood species				
<i>Picea excelsa</i> L.	14	42.3 ± 2.3	89 ± 12	542 ± 136
<i>Pinus sylvestris</i> L.	12	44.2 ± 2.9	141 ± 19	527 ± 98
<i>Quercus robur</i> L.	13	41.4 ± 3.9	170 ± 28	574 ± 56
<i>Fagus syvatica</i> L.	16	43.1 ± 4.8	192 ± 36	559 ± 74
Chips from SRC				
<i>Salix viminalis</i>	12	48.9 ± 3.8	364 ± 46	534 ± 86
<i>Robinia pseudoacacia</i>	12	36.1 ± 2.8	574 ± 64	526 ± 116
Crushed bark of trees				
<i>Picea excelsa</i> L.	8	49.3 ± 4.8	309 ± 36	532 ± 64
<i>Quercus robur</i> L.	16	46.8 ± 4.1	415 ± 58	558 ± 81

\* the mean value is the result of three half-hour measurements at each operator.



**Figure 1.** Dependence of the conversion factor of fuel-bound nitrogen into nitrogen oxide emissions on the content of nitrogen in dendromass in the process of combustion of moist dendromass in grate furnaces of heat generators.

The functional dependence relationship of the conversion factor of fuel-bound nitrogen into emission oxides ( $X_{\text{NO}_x}$ ), depending on the proportion of nitrogen in the dendromass combustible  $N^{\text{daf}}$ , is described by Equation (6):

$$X_{\text{NO}_x} = 15.439 \times \left(N^{\text{daf}}\right)^{-0.476} \quad (6)$$

with the index of determination being  $R^2 = 0.9692$ . A necessary condition for the validity of this dependence is that the temperature does not exceed  $1124^\circ\text{C}$  anywhere in the combustion chamber.

#### 4. Discussion

In our operating experiments the concentrations of CO in the flue gases (Table 3) confirmed that the dendromass combustion process was correctly regulated. The values of CO concentrations

were very stable, and the differences between the individual types of dendromass were negligible because the experiments took place under operational conditions. Boilers worked in real conditions and emission measurement was carried out during continuous operation of at least 90% of the boiler output. In all cases, the maximum concentrations of CO were significantly below the acceptable emissions limit values ( $850 \text{ mg/m}_n^3$ ). In contrast, the concentrations of nitrogen oxides differed significantly, which is certainly related to the differences in the content of fuel-bound nitrogen.

The calculated values of the conversion coefficient for fuel nitrogen in wood and bark to emissions of  $\text{NO}_x$ , and the dependence of the conversion coefficient of fuel nitrogen in  $\text{NO}_x$  oxides on fuel nitrogen content in woody biomass, can be considered as representative. This is justified by the conditions of combustion, emissions measurements performed and the technical calculation itself, and confirmed by further knowledge and findings.

According to Marutzky and Seeger [16] and Lin and Murase [17], the concentration of nitrogen oxides in combustion gases from combusting dendromass is also affected by nitrogen-containing adhesive and chemical protectants contaminating the wood. The emission of  $\text{NO}_x$  is higher during particleboard and glued veneer combustion than it is during the combustion of wood without additives [18]. For this reason, we avoided possible uncertainties of this nature in our experiments. In areas of timber harvesting, no chemical interventions or treatment of forest stands had occurred in the past or during timber harvesting. The chips, sawdust, and bark prepared for the experiment may be considered standard biofuels [19].

All measurements of the concentrations of nitrogen oxides in combustion gases for determining the conversion coefficient were performed during stable operation of the combustion devices and at a minimum power of 90% of the rated power. This minimizes uncertainty in establishing concentrations of  $\text{NO}_x$  in combustion gases and the values of conversion coefficients.

Although  $\text{NO}_x$  was found to be formed mainly by the conversion of fuel-bound nitrogen, an important precondition for determining the correct value of the conversion coefficient of fuel-bound nitrogen into nitrogen oxides was making sure that only fuel-bound nitrogen oxides would be formed. Biomass feedstock can burn with water contents up to 60% [20]. Hence we combusted only dendromass with a humidity over  $W^r = 23\%$ , in which the adiabatic temperature of the flame of the combusted biofuel, in excess air  $\lambda = 2.1$ , was below the value  $t_{ad} = 1124^\circ\text{C}$  [21]. Similar data is given, for example, by Nussbaumer (2003) [22]. Maintaining an excess of oxygen in the combustion gases at values  $\lambda > 2.0$  was strictly adhered to and thoroughly controlled by emission measurements. By combusting only dendromass with moisture content between  $W^r = 33.3\%–54.1\%$ , we avoided creating conditions for the formation of high temperature and immediate nitrogen oxides in the boiler furnaces. Based on the mechanism of oxidation of fuel C and N, it follows that with improved oxidation conditions, the concentration of CO falls and the concentration of  $\text{NO}_x$  increases in combustion gases. This was confirmed in practice [5].

Nitrogen content was the lowest in coniferous wood and approximately two to three times higher in deciduous trees. Nitrogen content was higher in the bark and chips, and was highest in SRC. The difference between the lowest nitrogen content, in the wood of *Picea excelsa* (L.) (0.04%), and that in the bark of *Robinia pseudoacacia* (3.52%) was almost 100-fold. This is consistent with the theoretical values of the maximum concentrations of nitrogen oxides if all the fuel-bound nitrogen of the dendromass was converted to nitrogen oxides during combustion.

However, the real measured values of  $\text{NO}_x$  concentration in the combustion gases, converted to 11%  $\text{O}_2$ , were significantly lower than the theoretical values, ranging from  $77 \text{ mg/m}_n^3$  to about  $600 \text{ mg/m}_n^3$ . The relations between nitrogen oxide emissions of coniferous and deciduous trees are therefore similar to the values published in the literature [6,23].

Figure 1 shows a significant decline in the values of the conversion coefficient with an increasing proportion of nitrogen in the dendromass. The declining values of the conversion coefficient of fuel-bound nitrogen in the combustion process of wood is attributed to increased concentration of nitrogen oxide (NO) in the combustion chamber. A similar trend was observed in Pleckaitine

and Buinevicius's model (2011) [8], according to which conversion was expressed by the equation  $X_{\text{NO}_x} = 11.312 \times (N_K)^{-0.6196}$  (where  $N_K$  is the nitrogen content in fuel, expressed as a percentage). Another graphically similar shape was produced by laboratory measurements of biomass combustion in an electrically heated reactor, where obtained values were considerably lower than the generally recognized values [24]. It follows from this that the results of laboratory modeled experiments cannot always be used for accurate calculations in real practice. Moreover, for combustion of various woods, the change of the design of the secondary air inlets might lower the emissions of  $\text{NO}_x$  [25].

Our generalized results make it possible to determine the minimum concentrations of nitrogen oxides from combusting woody biomass in the grate furnaces of boilers, depending on the content of fuel-bound nitrogen. If, in one of the grate furnaces, higher concentrations of nitrogen oxides are created than those corresponding with Equation (4), which was derived by our experiments, then the operator can seek the causes of increased creation of nitrogen oxides and modify the parameters of combusting dendromass in grate furnaces in order to minimize nitrogen oxide emissions.

## 5. Conclusions

This paper describes extensive experiments on the operational combustion of specially prepared samples of eight kinds of dendromass with nitrogen content in the range 0.04%–1.26%, moisture content of  $W^t = 33.3\%$ –54.1%, and excess air  $\lambda = 2.1$ . Under these conditions, only fuel-based nitrogen oxides are released. Average concentrations of  $\text{NO}_x$  in dry combustion gases (converted to 11%  $\text{O}_2$ ) ranged from  $89 \pm 12 \text{ mg/m}_n^3$  (in chips and sawdust from debarked wood *Picea excelsa* L.) to  $574 \pm 64 \text{ mg/m}_n^3$  (in chips from SCR *Salix viminalis*). With an increasing proportion of nitrogen in the dendromass (combustible  $N^{\text{daf}}$  in the range 0.04%–1.26%), the conversion factor  $X_{\text{NO}_x}$  decreased according to the relationship  $X_{\text{NO}_x} = 15.439 \times (N^{\text{daf}})^{-0.476}$ .

Our analysis shows that approximately 2/3 of the fuel-bound nitrogen was converted into  $\text{NO}_x$  in the combustion of coniferous wood with a low nitrogen content (up to 0.1%). In the combustion of wood from deciduous trees with a nitrogen content above 0.1%, less than half of the fuel-bound nitrogen is converted into  $\text{NO}_x$ .

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