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The Effect of Mixing Recirculated Flue Gas with Primary or Secondary Air during Biomass Combustion in Grate-Firing Boiler as the Primary Measure for NO_x Reduction

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Abbreviations and symbols

NO_x – Nitrogen oxides; *FGR* – Flue Gas Recirculation; λ – Excess Air Ratio; *LHV* – Lower Heating Value; *PA* – Primary Air; *SA* – Secondary Air.

1. Introduction

Nowadays the approach of sustainable development and science consider thermal energetics as the performance and development of energy transformation, transportation and exploitation systems, while receiving energy by long-term conditions that are economically, socially and environmentally acceptable in modern society. In accordance with the EU Directive 2015/2193 [1], the aim is to broaden the extent of energy production from renewable energy sources, therefore, biofuel is increasingly used in the energy production. With the advancing technology of combustion of solid biomass and increasing demand of biofuel boilers, boilers of gas, diesel or other fossil fuels were increasingly substituted. One of the main reasons of the transition was development of solid biofuel boilers by increasing their efficiency, adjusting to stricter environmental regulations and utilizing forest or agricultural waste.

With the increasing use of biomass in energy production, all the available biomass resources will be utilized, as well as the resources not yet used because of their high emissions of pollutants by combustion. Thus, energetics of biomass currently has an important task of looking out for technological solutions to reduce the emissions of gaseous pollutants released in the atmosphere. New regulations of the emissions from medium-capacity combustion appliances were implemented in 2018 and stricted permissible norms of concentrations NO_x and SO_2 in combustion products 2 to 5 times, and 15 to 20 times to those of particulate matter. Some of EU countries have even stricter regulations of emissions of NO_x and other pollutants than the general EU regulations, for example, the permissible level of NO_x in the flue gas in some countries is ≤150 mg/m³, while EU norm is 300 mg/m³. Some of the regions with a greater level of pollutive activity have permissible level of concentrations of NO_x set to 70-100 mg/m³ or less. Therefore, in order to satisfy the norms new technologies of biomass combustion are necessary. These regulations occur because emissions are harmful to environment as these compounds are the major cause of acid rain, soil acidification, eutrophication and destructive environmental effects [2].

In order to utilize biomass as fuel, specific technologies of combustion are needed to ensure that the use of biomass of higher N content follows strict environmental regulations of EU and technological combustion problems are avoided. This study analyzes reducing NO_x by primary measure by implementing recirculation of flue gas (*FGR*) as mixture with the primary or secondary air. The fuels used for experiments were agriculture and forest waste, as well as high quality wood chips.

2. Literature review

2. 1. NO_x origins and ways to reduce emissions

NO_x emission control measures must be implemented to prevent their formation (primary measures) or to remove them from flue gas (secondary measures). Nitrogen oxides are mainly of the three types of nature: thermal NO_x, prompt NO_x and fuel NO_x [3]. Thermal NO_x usually forms, when combustion is carried out in temperature range higher than 1400°C and commonly occurring when natural gas, coal or fuel oil are combusted, while temperature of biomass combustion (woodchips, wood pellets) is not high enough to reach the temperature range of thermal NO_x formation. In most cases, biomass combustion is carried out by applying flue gas recirculation to further reduce the combustion temperature, therefore thermal NO_x generation for biomass combustion is uncharacteristic. Prompt NO_x is formed during the reaction of an incomplete combustion hydrocarbon radical with a nitrogen atom. This is a two-way reaction and the amount of prompt NO_x is negligible [4]. However, the biggest amount of NO_x is formed from fuel nitrogen *N* during biomass combustion in the process of oxidation of char-*N* and volatile *N* [5].

In small-scale biomass incineration plants, secondary measures are usually not economically viable, only primary measures are used. Primary measures include a wide range of methods, such as modification of fuel composition – co-firing [6], fuel particle size and type of combustion equipment design [7], excess air control, flue gas recirculation [8]. As for the secondary measures of emission reduction, using catalytic converter or selective non catalytic reduction and injection of chemical reagents [9] is expensive and requires additional equipment.

2.2. Emissions of fuel *N* with volatile substances

To keep the boiler running optimally and minimize emissions as much as possible, it is essential to understand the biomass fuel conversion in grate firing furnace. It is carried out in 4 stages: biomass drying-dehumidification, fuel heating and release of volatile substances and its combustion, fuel char combustion and ash formation. Upon heating, the thermally unstable molecules of organic compounds in the fuel decompose and gaseous decomposition products called volatile substances are released. The onset temperature and number of volatile substances depends on chemical composition of the fuel. The lower the degree of carbonation of the fuel, the more thermally unstable molecules it contains and the more volatile substances it emits. Most volatile substances are released from wood containing biomass - about 85% of its combustible mass [10].

Studies on fuel bound nitrogen conversion to NO_x mainly consist of 2 types: volatile *N* and char-*N* [11]. It has been concluded that NO_x concentrations are increasing significantly during fuel heating [12]. It is explained in other studies, that during pyrolysis of the biomass the 30% of fuel -*N* was released with volatile substances, when the temperature was raised up to 500°C. Consequently, thermal fuel processing is acceptable as one of the primary measures to reduce NO_x emissions [13]. Another experimental study states the conversion of fuel - *N* is highly reliant on the temperature and fuel - *N* content. 17–47% of the fuel- *N* was retained in the char during pyrolysis, when experiment was carried out in isothermally pyrolyzed horizontal tube reactor at the temperature range of 500–900°C [14]. It is possible to state that NO_x formation from volatile substances highly depends on the combustion temperature.

Besides, another studies [15] discuss that carrying out combustion with *CO* could increase the reduction of NO_x by the reaction:

$$NO + CO \rightarrow \frac{1}{2} N_2 + CO_2. \tag{1}$$

Although carbon monoxide is an indicator of the incomplete combustion, it is an appropriate tool. Some article states, the additives could be supplemented in the combustion zone that would release *CO*, while it would compete for O_2 molecule during the processes of nitrogen oxidation [13].

2.3. Flue gas recirculation impact on NO_x emissions

The reduction of NO_x emissions could be studied by burning biomass in gasification mode. It could be done by introducing flue gas recirculation to the combustion of biomass. The emissions in biomass combustion products that are limited by the new EU legislations for the rates of medium combustion plants are nitrogen oxides, while carbon monoxide emissions are no longer limited. A lot of studies propose that biomass combustion by burning it by gasification mode with recirculating flue gas is an appropriate way to reduce the NO_x emissions as a primary measure [4, 6, 16-19].

Another article states the NO_x and *PM* emissions could be reduced by introducing air staging and supplying flue gas recirculation in the grate firing biomass boiler of 200 kW capacity. Wood chips, wood pellets and miscanthus briquettes were used for the experiments. NO_x emissions were minimized in the reduction zone and an efficient flue gas burnout was achieved in the tertiary zone. The highlights of the article were the lowest NO_x emissions due to an air ratio in the secondary zone between 0.8 and 0.9 and supply of recirculated flue gas above the grate led to even lower NO_x emissions: a reduction by 39% for wood chips, 40% for wood pellets and 45% for miscanthus briquettes was achieved compared to typical small-scale furnace [17].

After reviewing the literature in which the experiments were performed on test stands, the following article is a review of a scientific article in which the experiments on NO_x reduction was performed using 12 MW industrial biomass furnace. Combustion in a gasification mode was performed by mixing primary air with recirculated flue gas and maintaining low air excess. The studies have shown that the lower the excess air ratio λ coefficient, the lower the NO_x values. The NO_x values decreased by 10% when decreasing air excess from 1.5 to 0.5, when the nitrogen content range in the fuel is 0.06-0.12% [18].

Not only are the experiments made to determine the NO_x emissions in the flue gas, but also numerical simulations of grate fired combustion were computed with *FGR* implementation. The authors of the following article state that the formation of fuel NO_x is very complex and sensitive to fuel composition and combustion condition and accurate predictions of fuel NO_x formation from biomass combustion rely heavily on the use of chemical kinetics with sufficient level of details. The authors used computational fluid dynamics together with 3 gas phase reaction mechanisms. The numerical simulations were compared with the experimental and showed good validity with a high nitrogen oxides reduction at a primary air excess ratio of 0.8, and it could be mixed with the recirculated flue gas [19].

As the NO_x reduction by using the biomass combustion in gasification mode is studied quite widely, reduction of the emissions of NO_x when the recirculated flue gas is mixed with the primary or secondary air still lack studies. The aim of this paper is to explore the tendencies of previously mentioned emissions by burning biomass and supplying flue gas recirculation to the different combustion zones.

3. Methods and research

3.1. Description of the experimental stand

The experimental research was carried out by using an experimental 25 kW biomass grate firing stand, which scheme is shown in Fig. 1. It consisted of 3 main parts: furnace, 2-stage experimental section and flue gas – water heat exchanger – boiler. The furnace and the boiler were scaled-down copies of common industrial facilities, however, their operation was identical to that of industrial biomass water heating boilers, as the stand was also equipped with automatic fuel supply system. The furnace of the stand had variable speed moving grate and accurate fuel and air supply was ensured by variable speed drives.

The combustion of fuel in the furnace generates hot combustion products, which are first directed to the experimental section (reactor). Both the furnace and the experimental section are adiabatic and not cooled, therefore the temperature of the combustion products reached does not exceed 900-1200°C, consequently, the temperature range is below of thermal nitrogen oxides generation temperature.

Combustion products enter the water-cooled heat exchanger (boiler), where, depending on the furnace load, they are cooled down to the temperature of 130-170°C, and then removed through a chimney with the help of the flue gas fans. Water heating boiler was made from steel, vertical, and shell-type with 2 flue gas passes. The water temperature in the boiler in the nominal operating mode reached ~65°C at the inlet and ~85°C at the outlet to prevent flue gas condensation and corrosion of the tubes.

This fuel burning stand can burn both dry and wet fuels of fraction size from 1 mm to 20-30 mm. The combustion stand has numerous options for combustion control – from ordinary to gasification mode. In the case of need to control primary, secondary air or their mixture with the recirculated flue gas individually by following the oxygen concentration at the outlet of the boiler, the stand is modelled to provide this possibility.

The scheme of the stand is given in Fig. 2.

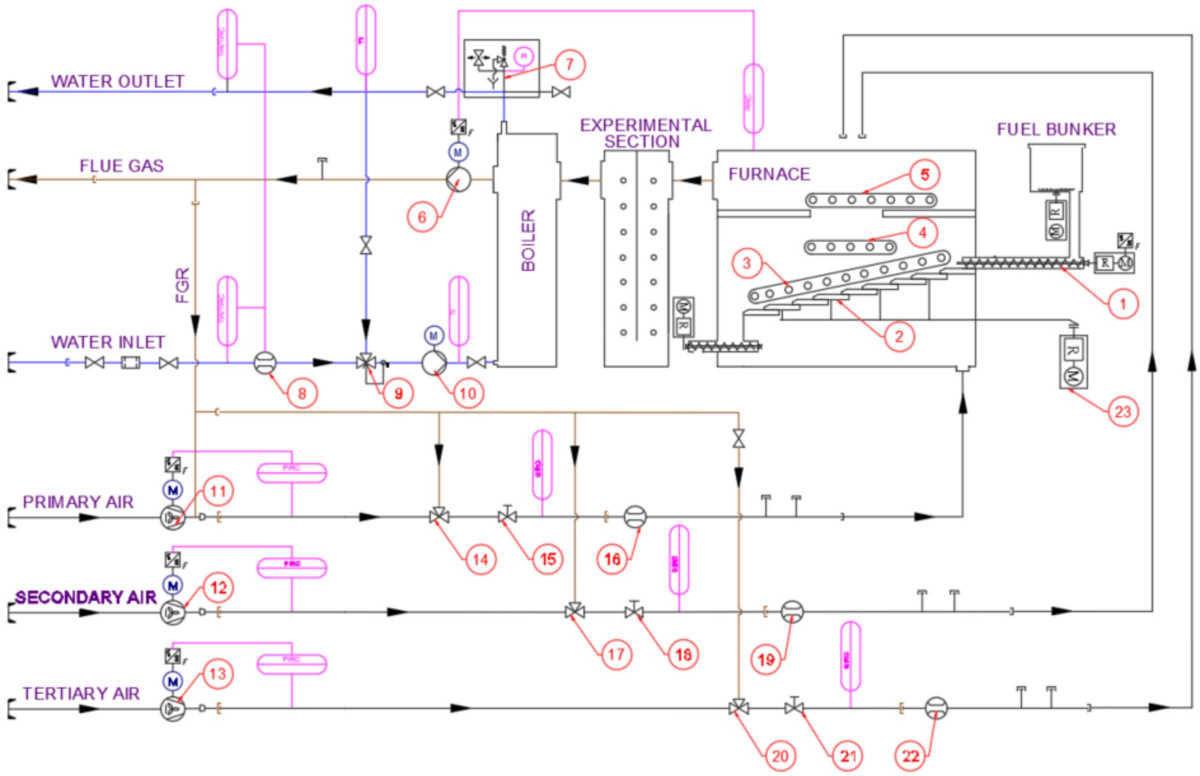

Fig. 1 Functional scheme of experimental stand used in this study: *1* – fuel screw conveyor, *2* – moving grates, *3* – orifices for air supply over fuel bed / temperature measuring, *4* – orifices for air supply under the arc / temperature measuring, *5* – orifices for air supply of final combustion zone / temperature measuring, *6* – flue gas fan, *7* – air vent/safety valve, *8* – water flowmeter, *9* – water mixing valve, *10* – water pump, *11* – primary air fan, *12* – secondary air fan, 13 – tertiary air fan, 14 – valve for mixing primary air with flue gas recirculation, 15 – balancing valve, *16* – portable air flowmeter, *17* – valve for mixing secondary air with flue gas recirculation, *18* – balancing valve, *19* – portable air flowmeter, *20* – valve for mixing tertiary air with flue gas recirculation, *21* – balancing valve, *22* – portable air flowmeter, *23* – electric moto for grate movement

3.2. Description of measuring devices

Various measurement devices for the experiments were used. Electrochemical cells MRU Vario Luxx were used. Electrochemical cells MRU Vario Luxx (MRU Messgerate fur Rauchgase und Umweltschutz GmbH, Neckarlsulm, Germany) and Multilyser Ste (SYSTRONIK Elektronik und Systemtechnik GmbH, Ilmensee, Germany) used for the flue gas emissions and oxygen concentration measurement. The MRU Vario Luxx was used for continuous emission measurements and loggings, mainly NO_x, NO, NO_2, SO_x, H_2S, CO, CO_2, temperature and O_2 content of flue gas. The oxygen content of the sample gas was measured with 2-electrode electrochemical sensor, while the emissions were measured with 3-electrode electrochemical sensor, based on gas diffusion technology.

Also, the Multilyser Ste was used, that could measure the oxygen content in the flue gas, its temperature and emissions such as NO_x, SO_2 and CO. This analyzer was used for recirculated flue gas measurements.

Both MRU Vario Luxx and Multilyser Ste measurements were converted to the standard oxygen content in the flue gas $O_2 = 6\%$ ($\lambda = 1.4$).

Finally, to keep the air flow appropriate for the combustion, it had to be evaluated. For the primary, secondary and recirculated flue gas flows measurements the Hoentsch portable device was used. It consisted of flow measuring probe with cylindrical vane wheel sensor ZS25 ZG1, which is appropriate for measuring flue gas and air flows flows due to its characteristics of measuring range and temperature range, which is up to 500°C. Also, the data. Also, the data logger handheld flowtherm NT.2 is essential for flow measurements as it simultaneously displays the flow, velocity or temperature measurement results and has the ability to export the data to other devices.

3.3. Characteristics of fuel used for experiments

The experiments were carried out by burning various fuel with different chemical composition, by burning them separately. These fuels were sunflower husk pellets, shredded pine bark and wood pellets. Sunflower husk pellets were chosen because it has higher nitrogen content compared to wood chips and it is among the largest forms of agriculture waste in Europe. Moreover, it should be used more widely as fuel to achieve the energy independence from fossil fuels. Shredded pine bark was used because it also has higher *N* values and corresponds to inferior quality wood waste, consumption of which also needs to be increased in energy sector. Wood pellets were also used for comparison as it has the minimal *N* values in its composition and meets the higher quality of wood fuel.

Due to the *N* presence in these fuel species, NO_x emissions are generated in the flue gas. The dependence of these emissions on the type of fuel and the impact of *FGR* with the primary or secondary air mix was investigated. The physical and chemical properties, like *N* content in the fuel and the fuel moisture were determined in accredited laboratories. in accredited laboratories. The chemical composition of nitrogen was determined based on the EN ISO 18134-1:2016 standard [21]. The physical properties of the fuel moisture were determined by the EN ISO 18134-1:2016 [22]. The major fuel characteristics are presented in the Table 1 as the dry fuel matter.

Table 1

Characteristics of the fuel used for experiments

Fuel	Moisture	Nitrogen in dry mass, N
	%	%
Sunflower husk pellets	8.6	0.73
Shredded pine bark	47.2	0.39
Wood pellets	5.9	0.15

4. Research methodology

The aim was to compare the effect of *FGR* in reducing the emissions of NO_x, when it was mixed with primary or secondary air. At the beginning of the furnace grate, fuel was heated up, at the second part of the grate the volatile substances were released (about 85 % of the fuel), while at the third part, the rest of the fuel – coke was burned. At the end of the grate, there was only ash which fell off the grate to the ash removal part with the ash screw conveyor.

The experimental furnace concept is designed for a wide range of air distribution. There were 27 symmetrical orifices on both sides of the furnace for possible air or recirculated flue gas supplying. The arrangement of the orifices, fuel inlet position, primary air inlet, flue gas outlet, front and back arc is given in Fig. 2.

In the different levels of the furnace, air, *FGR* and their mixture can be introduced. Depending on the point of their entry in the furnace, the relevant combustion process affected and the formation of NO_x. It is known that part of fuel nitrogen starts to form *NO* in the fuel bed, when hydrocarbons split and oxidize. However, a large concentration of incomplete combustion products is present in this primary zone, thus a significant competition for the free oxygen occurs and only a part of *NO* is formed. The other part of *N* is released with the volatile substances that take longer to burn in the second combustion zone. The formation of the fundamental part of *NO* occurs in this oxidation zone. There is a third combustion zone, where the main combustion processes are already completed, but a reaction between *CO* and *NO* is still happening, where breakdown of *NO* and oxidation of *CO* to CO_2 takes place. The stand has a long isothermal channel, where breakdown of *NO* occurs, if combustion products contain *CO*.

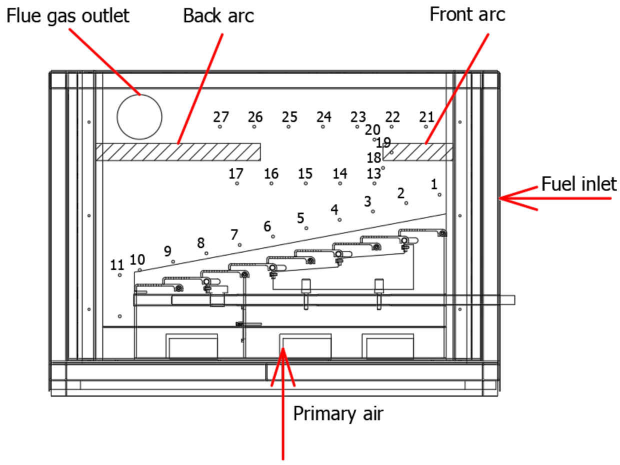

Fig. 2 Arrangement of the internal parts of the furnace

Depending on where and which agent is inserted through level I-III orifices, the influence is made on the processes of the 1st to 3rd zone, where the level I is 3-7, level II is 13-17 and level III is 22-26 orifices:

1. Insertion of recirculated flue gas with primary air slows down combustion reactions by lowering the concentration of O_2 in the fuel bed and lowering the combustion temperature. Combustion process is extended.
2. Insertion of recirculated flue gas through orifices to the fuel bed should also slow down combustion reactions of volatile fuel gasification products and reduces formation of *NO*. Insertion of air through orifices I facilitates combustion reactions and should result in an increase of *NO*.
3. The main combustion processes are partly completed in the level of orifices II, the insertion of recirculated flue gas and air through these orifices should have the same effect as in the case of orifices I, but weaker.
4. The combustion processes in the level of orifices III are mostly completed, therefore *NO* level here should depend on what increases the concentration of *CO*. For example, the insertion of recirculated flue gas aggravates the burnout of *CO*, thus *NO* has to be decreased. The insertion of air has to increase level of *NO*, because in that way oxidation of *CO* is facilitated.

The air and *FGR* distribution were ensured in several ways. The primary air or primary air and flue gas recirculation mixture were always supplied under the grate. The secondary or secondary air mixture with flue gas recirculation or recirculated flue gas independently could be supplied through 3-7, 13-17, 22-26 orifices. Initial experiments suggested that the results between 3-7 and 13-17 orifices were quite similar because of the short distance between them and it did not influence the combustion as both times air flow was above fuel bed, but under the arcs. Besides, the *FGR* and secondary air mix supplying above the arc did not have any significant impact on NO_x reduction. Consequently, the air and recirculated flue gas through 13-17 and 22-26 orifices were rejected for the main experiments.

Therefore, the experiments were performed by changing air and *FGR* distribution in different 2 variations: the 1st option was introducing primary air and *FGR* mixture under the grates, while secondary air was supplied above the arc through 22-26 orifices. The 2nd option was by supplying primary air under the grate, while *FGR* and secondary air was supplied through symmetrical 3-7 orifices. The amount of recirculated flue gas was adjusted in accordance with the rate of O_2 in the mixture, while the rate of O_2 was gradually reduced by 2% from 21% (*FGR* = 0) to 13%, (*FGR* = max) as it was carried out, when the primary or secondary air and recirculated flue gas were mixed. Also, an experiment with the lowest possible level of oxygen in secondary air - *FGR* mixture was also performed. It was expected the combustion would be inhibited and the nitrogen oxides decreased.

All studies were performed ensuring the conditions are as stable as possible and maintaining the same fuel delivery rate for the same fuel type. Draft inside the furnace tended to maintain the same for all experiments – about -5 Pa. The capacity of the boiler was 20-25 kW when burning dryer and more calorific wood and sunflower husk pellets (*LHV* was 18140 kJ/kg and 17550 kJ/kg, respectively), and about 5 kW when burning wetter and less calorific fuel of shredded pine bark (*LHV* – 8670 kJ/kg).

5. Results and discussion

5.1. Experiments of NO_x reduction

Research of emissions of NO_x while burning different types of fuel by mixing primary or secondary air and *FGR* lead to the results shown in Figs. 3-5.

The graphs are sorted by different types of fuel combusted. During the tests, the primary or secondary air and the recirculated flue gas were mixed by downgrading O_2 content in its mixture as stated previous. The proportion of the primary or secondary air/recirculated flue gas mix and the secondary air was maintained 1:1.3 respectively. The highest excess air rate λ in the flue gas to stack was by supplying primary or secondary air without flue gas recirculation, and the lowest O_2 rate was by the highest recirculated flue gas. Excess air ratio in the flue gas to stack was in the range λ = 1.4-1.9.

The results of the experiment by burning higher fuel - *N* fuel sunflower husk pellets shown in Fig. 3, showed quite different tendencies of NO_x. In the first case, when the primary air was mixed with the *FGR*, significant results of reduction of NO_x were obtained. The NO_x emissions changed from 431 mg/nm³ to 367 mg/nm³ and it was reduced by 15%, when the O_2 in the mixture decreased from 21% to 13%. The reduction in NO_x is likely to have been achieved by slowing down the combustion of NO_x in the first zone as it was analyzed in literature review [18]. Different results of reduction of NO_x were observed when the secondary air was mixed with the *FGR*, as its average values did not change along the experiments. It fluctuated between the 432 mg/nm³ and 442 mg/nm³. It can be assumed that the main combustion processes had already taken place in the primary combustion zone and the suppression of combustion above the fuel layer did not affect the NO_x reduction. Nonetheless, an additional experiment of decreasing O_2 level in the secondary air and recirculated flue gas mixture as low as the equipment allowed – till the O_2 = 8%, was conducted. In that case, the NO_x emissions were reduced by 21% to 342 mg/nm³. On the contrary to previous findings, it can be assumed that in order to achieve significant results of nitrogen oxides reduction by mixing secondary air with *FGR*, it needs to decrease oxygen level more than in primary air and *FGR* mixture to reach the similar significance results. These results are in agreement with previous studies [17].

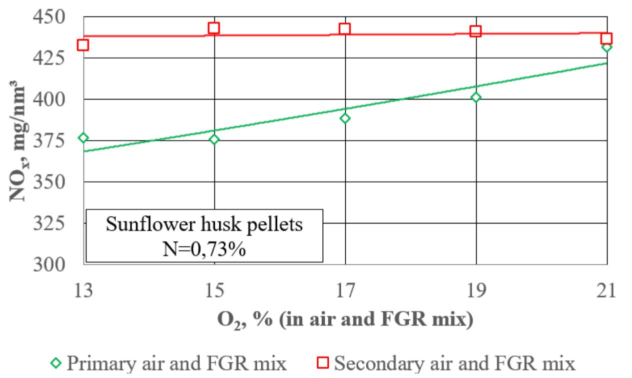

Fig. 3 The effect of mixing recirculated flue gas with primary or secondary air on NO_x emissions by burning sunflower husk pellets

The results in Fig. 4 show the tendencies of NO_x when burning shredded pine bark of average fuel- *N*. The impact of the primary air and *FGR* mixing is greater than that during burning of sunflower husk pellets. In this case, the NO_x emissions were reduced by 29%, from 305 mg/nm³ to 216 mg/nm³. Also, the effect of the secondary air and *FGR* mixture was studied and it showed lower but still significant reduction of NO_x by 25% from 204 mg/nm³ to 152 mg/nm³. The reduction in NO_x in both cases can be explained by the fact that the biomass fuel was very moist (47.2%) and the combustion process took much longer. Therefore, *FGR* and secondary air mixture also influenced NO_x as it enters the combustion zone.

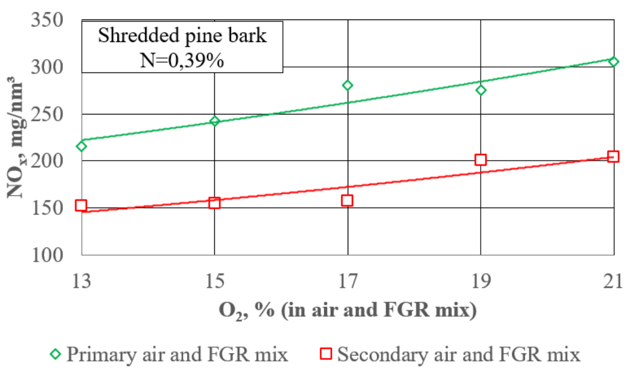

Fig. 4 The effect of mixing recirculated flue gas with primary or secondary air on NO_x emissions by burning shredded pine bark

Finally, the results of combusting fuel of the lowest fuel - *N* – woodchip pellets are given in Fig. 5. Compared to the previous results of combustion, it is quite contradictory because the slowing down of the combustion in the primary phase by supplying primary air and *FGR* mix under the grate gave the NO_x reduction of 4%, from 129 mg/nm³ to 124 mg/nm³. When the *FGR* is mixed with secondary air, significant results regarding the change of NO_x also were not achieved, as it was reduced by 6%, from 137 mg/nm³ to 129 mg/nm³. It can be argued that reducing NO_x with low *N* fuels is inefficient, as emissions from such fuels are low enough. Similar to the case of sunflower husk pellets, an additional experiment of decreasing O_2 level in the secondary air and *FGR* mixture as low as the equipment allowed – till O_2 = 8% was conducted. In this case, similar results to those with different fuels were achieved, as the emissions of NO_x were reduced by 40% to 80 mg/nm³. Again, it can be assumed that in order to achieve significant results on nitrogen oxides reduction by mixing secondary air with *FGR* it needs to decrease oxygen level more than in primary air and *FGR* mixture as the main combustion processes are already completed, but a reaction between *CO* and *NO* is still happening, where breakdown of *NO* and oxidation of *CO* to CO_2 takes place [4].

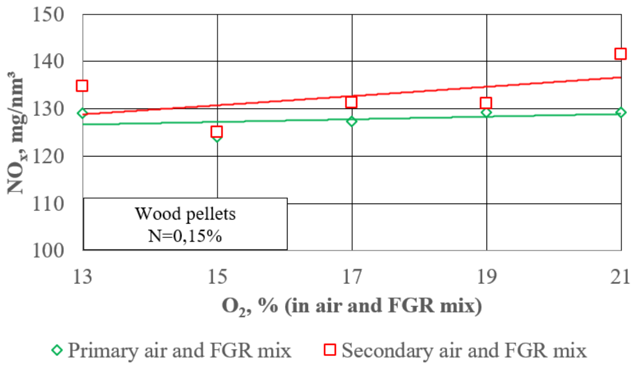

Fig. 5 The effect of mixing recirculated flue gas with primary or secondary air on NO_x emissions by burning wood pellets

5.2. Comparison of different NO_x reduction methods

The comparison of various fuels by using different methods of *FGR* mixing with primary or secondary air is presented in Figs. 6-7. The ratio of NO_x to $NO_x^{R=0}$ (*FGR* = =0) is given in the graphs, where NO_x represent the value of the nitrogen oxides at the exact point of the O_2 level in the *FGR* and the primary or secondary air mixture and the $NO_x^{R=0}$ stands for the point, where no *FGR* is supplied. The ratio value of <1 indicates the reduction of NO_x, while value of ≥1 means the emissions increased or did not change.

The results of the Fig. 6 showed the *FGR* adding to primary air is a promising way of NO_x reduction for the fuels with higher *N* in its composition. The reduction ratio of sunflower husk pellets at the lowest O_2 point was 0.85 and for the shredded pine bark – 0.71. However, the same could not be stated about fuel with low *N* composition. The lowest ratio was 0.96, indicating non-significant results. As known from previous research [19], the *FGR* supplying and mixing with the primary air should slow down the combustion, the incomplete combustion product is formed and it competes for the free oxygen with the fuel *N*, consequently its conversion should be lowered. However, the experiments showed that the efficiency of this method is minimized, when low-nitrogen content fuel is combusted.

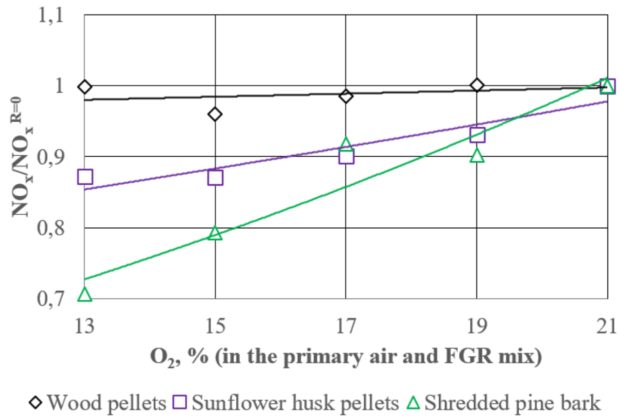

Fig. 6 The influence of mixing of primary air and recirculated flue gas on NO_x emissions from different fuels

The same ratio as in Fig. 6 was also studied in Fig. 7, when the *FGR* was mixed with the secondary air. The results were divided in the groups of the fraction of the fuel: pellets and loose shredded pine bark. Also, the reduction of emissions of NO_x did not depend on the *N* content in the fuel, but the lowest ratios were reached, when the O_2 =13% in the mixture of the *FGR* and secondary air. The ratio of sunflower husk pellets hardly changed, while the ratio of wood chip pellets decreased to 0.94. The lowest ratio of 0.75 was achieved by burning shredded pine bark. As shredded pine bark was loose fuel and it had the highest water content, it could be stated, that because of the longest fuel drying process, the main combustion reactions were not as fully occurring as in the case of other fuels in the first zone, therefore supplying the mixture of secondary air and *FGR* above the fuel bed had more significance for the reduction of emissions of NO_x, as the oxidizing reaction of the *N* was still relevant and taking place, while incomplete combustion products competed for the free oxygen molecules [14].

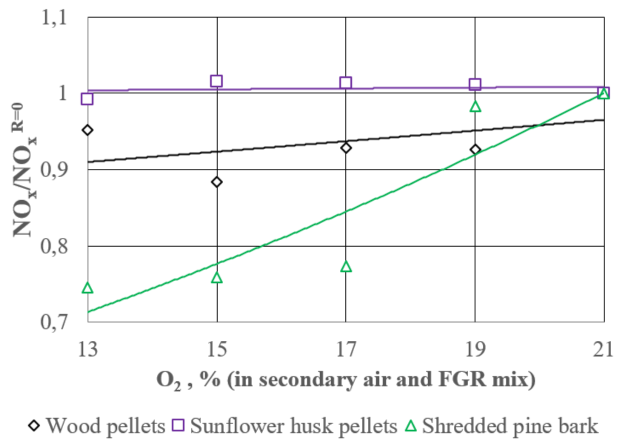

Fig. 7 The influence of mixing of secondary air and recirculated flue gas on NO_x emissions from different fuels

6. Conclusion

1. Study analyzed biomass combustion by implementing flue gas recirculation to primary or secondary air. The experiments were carried out by burning 3 types of biomass fuel of different *N* content in its composition: sunflower husk pellets (*N* = 0.73%), shredded pine bark (*N* = =0.39%) and wood pellets (*N* = 0.15%). The emissions of NO_x in combustion products of these various biomass were

analyzed. The results of experimental research showed some significant improvements in reduction of emissions, when the O_2 level in the *FGR* and air for combustion mixture was decreased.

2. The most recurring and promising results of NO_x reduction was when the primary air and *FGR* mixture with O_2 =13% was supplied under the grate. By combustion of sunflower husk pellets the NO_x emissions were reduced by 15%, while the emissions during the combustion of shredded pine bark and were reduced by 29%. The supplying of secondary air and the *FGR* mixture above the fuel bed with the same proportion had less positive results: emissions of shredded pine bark had the greatest reduction result of 25%.

3. This study has shown that the methods used in the experiments could be used to comply with EU standards of $NO_x \leq 300$ mg/nm³ emissions by burning shredded pine bark. However, the emissions of the sunflower husk pellets with the highest *N* content were not reduced enough to meet the required limits. The possible ways for higher reduction of NO_x for agriculture waste is supplying pure flue gas recirculation or/and mixing it with the lower *N* composition fuels.

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THE EFFECT OF MIXING RECIRCULATED FLUE GAS WITH PRIMARY OR SECONDARY AIR DURING BIOMASS COMBUSTION IN GRATE-FIRING BOILER AS THE PRIMARY MEASURE FOR NO_x REDUCTION

S u m m a r y

Due to the pollutant regulations of the Directive (EU) 2015/2193, the need to reduce the emissions of pollutant compounds such as NO_x is of a great importance for industrial boilers. This study was performed to determine the effect of primary measures in reducing said pollutants by mixing primary or secondary air with *FGR* and supplying the mixture for combustion. The studies were conducted on low-scale industrial biomass grate-firing furnace and boiler stand of 25 kW. Sunflower husk pellets, shredded pine bark and wood pellets were combusted during these experiments and emissions of NO_x in their combustion products were analyzed. The most significant reduction of emissions was achieved by mixing primary air and *FGR* and supplying it to the primary combustion zone – under the grate. The emissions of NO_x were reduced by 29% and 15% for shredded pine bark and sunflower husk pellets respectively. The emissions of shredded pine bark were reduced enough to meet the standards of the EU Directive, unlike those of sunflower husk pellets. The possible ways to reach greater reduction of NO_x by using primary measures are implementing staged combustion, supplying pure *FGR* and/or mixing agriculture waste with fuels containing less *N* in its composition.

Keywords: biomass, emissions, primary air, secondary air, flue gas recirculation (*FGR*), NO_x.

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