Grate-Firing Boilers Grate Movement Impact onto NOx, SO₂ Emissions

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Abbreviations and symbols

PM − Particulate Matter; SNCR − Selective Non-catalytic Reduction; DEM − Discrete Element Method; LHV − Lower Heating Value; NDIR − Non-dispersive Infrared Detector; FTIR − Fourier Transform Infrared Spectrometer; CEMS − Continuous Emission Monitoring System; λ – Excess Air Ratio.

1. Introduction

The use of solid biofuels - forest residues, wastes from the wood, agriculture, food industry and other biomass is one of the most effective ways to achieve renewable energy development goals and reduce the greenhouse effect. Due to the relatively fast recovery of biomass compared to fossil fuels, biofuels are considered a renewable source. The use of biofuels for energy production ensures a natural carbon cycle in the ecosystem.

The biomass chemical composition is significantly different from that of fossil fuels. Particular emphasis should be paid to nitrogen and sulfur. The N content in biomass can be as high as a few percent, which is typical of some wastes from the agricultural and furniture industry. High N content in fuels has been found to cause high NOx concentrations during fuel nitrogen oxidation processes. There is a clear correlation between N content in fuels and NOx emissions [1]. Comparative NOx reduction studies [2] have shown that NOx concentrations can be reduced by a variety of measures but only to a certain extent.

Numerous studies have been performed on the relationship between the sulfur content of fuels and SO_2 concentrations. It is a well-known law that the higher the sulfur content of the organic compound in the fuel the higher the expected SO_2 concentration. However, this dependence is far from linear and highly dependent on various combustion regime parameters.

In order to reduce emissions, the main goal is to reduce emissions by primary measures, i.e., prevention of emissions. This applies to various emissions. Secondary measures "clean" combustion products from the already formed pollutants - NOx, SO_2, and particulate matter (PM). These methods are often more expensive than primary ones.

With the entry into force of the new EU directives (2010/75 and 2015/2193) limiting the concentration of pollutants in products, it is clear that major part of biofuel combustion plants is facing difficulties in implementing these directives. In some countries, NOx concentrations are subject to even stricter requirements, e.g. as in the Netherlands and Sweden. As emission standards become more stringent, it is necessary to improve pollution abatement and flue gas treatment measures.

A real-time measurement and recording of pollutant concentrations with high-speed devices has revealed that pollutant concentrations are very unstable over time. Concentrations of certain chemical compounds and particulate matter at biofuel boiler flue gas can vary within relatively large limits. Measurements have shown that emission concentrations can vary by 30-50 %, even under stable boiler loads. Due to such significant fluctuations in flue gas concentrations, it is difficult to apply effective measures to reduce emissions, e.g. SNCR for NOx reduction due to time lag.

Reciprocating grate is commonly installed in waste incineration plants. However, this type of grate is also widely used in biofuel boilers, including for the incineration of agricultural waste [3]. Kruggel- Emden et al. simulations with the discrete element method (DEM) has been done by creating digital model of fuel combustion on the grate. That allows estimating the movement of fuel on the grate [4]. The simulation of the grate with simplified shape particles showed that the mechanical movement properties of the reciprocating grate along with the height of the fuel bed has significant impact for fuel mixing and combustion quality. DEM method also was carried by Sun Liyan et al. [5]. The temperature of the fuel cells was found to rise along with the movement and amplitude of the grate. Other research has shown that modeling of the spherical shape fuel particles motion can predict experimental results quite accurately [6].

Detailed studies of pyrolysis and combustion products in a reciprocating grate boiler [7] investigate the influence of combustion parameters and process location on grate. The results of modeling and experimental measurements demonstrated compliance between modeling the fuel bed height, temperature and pyrolysis gas evolution. In a 4 MW biofuel boiler the composition of combustion products inside the combustion chamber was studied at various distances from the grate surface and the fuel supply point [8]. A correlation was found between the primary air flow and the gas composition of the combustion products.

The influence of grate movement on O_2, CO, NOx concentrations can be seen in several research [9 – 11]. X. Zhang et al. [9] performed emission measurements and mathematical modeling on 320 kW wood chip boiler of a district heating plant. Measurement of emissions showed that O_2, CO_2 and CO concentrations fluctuated significantly during one-hour sampling duration. Oxygen concentration changed by 1.1%, CO_2 by 1.5% and CO by 300 ppm. CO emissions are even greater after recalculation to a standard reference oxygen (O_2 - 6%) and reach fluctuations from 682

to 2182 mg/m^3. The author himself associates these emission jumps with fuel supply mechanical processes.

Emission instabilities have also been observed by O. Sippula et. al. [10]. Measurements were performed in the 500 kW pellet boiler for heating of the school building. The periodicity of emission fluctuations was abundantly seen during combustion of lower quality biofuel made from bark. The fluctuations of O_2 and CO emission concentrations were 6% and 2000–5000 mg/MJ, respectively. At the same time an influence to particle number emissions and mean diameter were detected (Fig. 1).
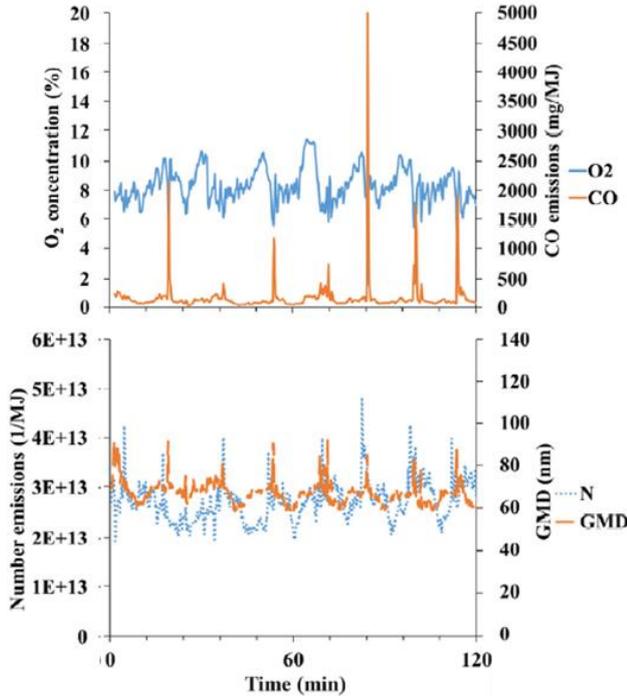
Fig. 1 Time series of O_2, CO, particle number emissions and particle number mean diameters during combustion of bark pellets [10]

The levels of O_2, CO, particle number mean diameter and emissions clearly shows a fluctuation that has a periodicity of 15–20 min. Familiar pattern was earlier observed by J. Leskinen et al. [11]. These mentioned authors attributes oxygen and incomplete combustion compounds emission instabilities to the fuel feeder and movement of the grate.

Two theories are distinguished that explain why changes in emission concentrations predominate during combustion process thus far. First one is that movement of the grate causes intensive gasification during which incomplete combustion products can be released [10]. It is clear that incomplete combustion is caused by a lack of oxygen. It must be defined that X. Zhang et al. [9] also notes that emissions are significantly affected by the excess of air. Second one is that during grate movement a portion of fuel is removed from blocking of primary air inlets (grate bar slits) [11].

Nevertheless, these extensive numerical modeling and experimental studies of fuel movement do not investigate the influence of grate movement on pollutant concentrations in detail and this issue has not been sufficiently explored.

This article is intended to determine the influence of movement of reciprocating grate on the fluctuations of gaseous and particulate matter pollutants concentrations. The research was performed in industrial 4 and 8 MW biofuel boilers and an experimental (20 kW) boiler.

2. Materials and methods

2.1. Description of the boilers

Experimental research was performed on Kaunas University of Technology 20 kW small-scale industrial biofuel boiler model together with 4 and 8 MW industrial boilers. The combustion parameters of this experimental model are close to conventional industrial biofuel boilers and have the same basic characteristics.

The industrial boilers and experimental boiler model consist of a similar two-stage combustion chamber plated with chamotte walls (Fig. 2). The air is distributed into different locations of the furnace. Primary air is supplied under the grate and passes through the slots between the grate bars. Primary air initiates and supports the combustion process on reciprocating grate and above the fuel bed, i. e., primary combustion zone. Secondary air is supplied to the upper part of the furnace, just before the secondary combustion zone. The vault separates the primary and secondary combustion zones. This allows to prolong the path of combustion products and extends oxidation time of volatile matter. Secondary air nozzles are located in the side walls. The secondary air ensures a complete mixing and oxidation of gaseous products.
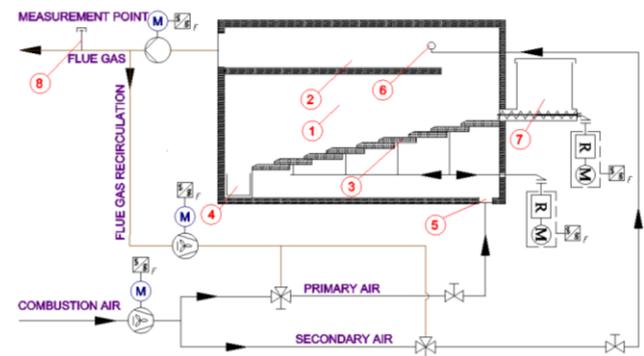
Fig. 2 A simplified schematic view of industrial and experimental model of biofuel boilers: *1* – primary combustion zone; *2* – secondary combustion zone; *3* – reciprocating grate; *4* – ash pit; *5* – supply of the primary air; *6* – supply of secondary air; *7* – supply of solid biofuel; *8* – gaseous emissions and particulate matter measurement point

In the experimental boiler model, biofuels are fed to the combustion chamber from the bunker by a screw conveyor. A stoker pusher mechanism is used for the industrial 4 and 8 MW biofuel boilers. Once in the furnace, the biofuel is distributed on a reciprocating grate, controlled by hydraulic cylinders (Fig. 3).

The grate consists of consecutively arranged stationary and moving rows of grate bars. Stationary rows of gratings are attached to a fixed grate frame that is marked in blue color. The remaining rows of gratings are attached to a horizontally back and forth sliding frame that is marked in red. Solid biofuel is pushed by moving rows of grate bars onto the stationary grates below. When the rows of the moving grate retract, the empty areas of the fuel bed are filled

with a new portion of biofuel. The process is repeated regularly. The remaining unburned inorganic material - the ash is removed from the furnace.
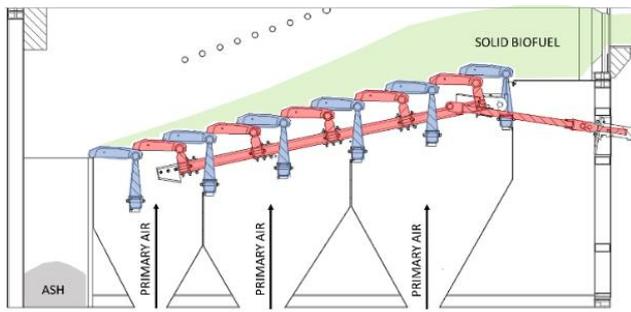
Fig. 3 A simplified schematic view of reciprocating grate

2.2. Fuel

Three fuels were burned during the study. Wood pellets and sunflower husk pellets were burned on experimental boiler model. The wood pellets met the requirements of ENplus-A1 class 6 mm pellets. Sunflower husk pellets (abbreviated as sunflower pellets) are produced from agricultural waste. Sunflower pellets size 8 mm. Wood chips burned in industrial 4 and 8 MW boilers. It is assumed that the wood chips with same properties was consumed for both industrial boilers. Typical physical and chemical values of biofuels, used in the study, are showed in Table 1.

Table 1

Characteristics of test specimens

Fuel	LHV, MJ/kg	Ash, %	Moisture, %	N, %	S, %	Cl, %
Wood pellets	17.10	1.2	8.7	0.20	0.01	0.02
Sunflower pellets	16.03	2.9	8.6	0.51	0.08	0.04
Wood chips	8.25	2.9	48.5	0.41	0.01	0.01

Wood chips made from forest residues have a low net calorific value (LHV). Fuel analysis show that the calorific value is as twice as low as pellets made from wood and sunflower and reaches 8.25 MJ/kg. This calorific value is reduced by the high moisture content of the fuel. A significant part of the energy is used to evaporate the moisture during combustion process. However, in the presence of a condensing economizer at the industrial biofuel boiler plant, this wasted energy can be recovered. Analytical studies ofthe chemical composition show that the average nitrogen content in wood chips is twice as high as in wood pellets. The higher proportion of bark, needles, leaves and other impurities in wood chips results a higher N content compared to wood pellets. Forest residues is also characterized by a certain proportion of soil and other inorganic impurities, resulting in higher ash content. In some cases, even higher quantities of S and Cl are possible.

2.3. Experimental procedure

During the case of 8 MW water heating boiler pollutants monitoring, CO, NO, NO_2, SO_2 and HCl were measured with a Fourier transform infrared spectrometer (FTIR) GASMET DX4000. Oxygen concentration was measured using a zirconia oxygen sensor Siemens Oxymat 61.

The O_2 and NOx concentrations in the 4 MW water heating boiler flue gas were measured with a continuous emission monitoring system (CEMS) Siemens ULTRAMAT 23. O_2 concentrations were measured with an electrochemical cell. NO concentrations measured with a non-dispersive infrared detector (NDIR). NO values were subsequently converted to NOx.

CO, NO, NO_2, SO_2, H_2S and O_2 emissions were measured in 20 kW experimental boiler model using an MRU Vario Luxx electrochemical cell analyzer. At the same time, PM emissions were measured using an Afriso STM 225 optical laser analyzer showing real-time concentrations.

All analyzers extract flue gas samples through heated hoses, have integrated coolers and condensate pumps. This ensures that no condensate forms and that no soluble gas (e.g. SO_2, NO_2) dissolves during sampling. In all cases, the measurements were performed at a constant boiler power load. The measured emission concentrations are reported to be recalculated under standard conditions at $O_2 = 6\%$.

3. Fluctuation of emissions in biofuel boilers

3.1. 8 MW biofuel boiler emissions

Emission instability was observed during emission measurements in an industrial 8 MW boiler. At constant boiler power load, flue gas, masonry temperatures and supply air volumes, a particularly large jump in the levels of O_2, NO, NO_2, NOx and HCl concentrations was observed. As can be seen in Fig 4., the results of the emission monitoring show clear jumps in the concentration of oxygen and nitrogen compounds. These fluctuations indicate the periodicity of the emission concentrations, averaging 45 to 68 s.

Experimental data (Fig. 4) were collected by continuous measurement and averaging the results every 20 seconds. The amplitudes of the fluctuations in different emissions vary. To estimate the numerical value of the change in these emissions, the standard deviation of the results is calculated with equation 1.

$$s = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(x_i - \bar{x})^2} \ . \tag{1}$$

The standard deviations of all emissions were found to depend on the average of the emission values. The higher the average emissions of the component, the higher the standard deviation, as shown in Table 2. This correlation is not clear for SO_2 emissions. SO_2 concentrations were detected only once and amounted to 7.37 mg/Nm³. For this reason, the average value of SO_2 is close to 0 mg/m³.

NOx concentrations were particularly unstable. These emissions ranged from 45.51 to 348.32 mg/Nm³. Due to the high temperature, relatively high O_2 content and good gas mixing in the final, i.e., secondary combustion zone, sufficient combustion is ensured. For this reason, no CO was detected, so these values are not shown in Fig. 4 for clarity.
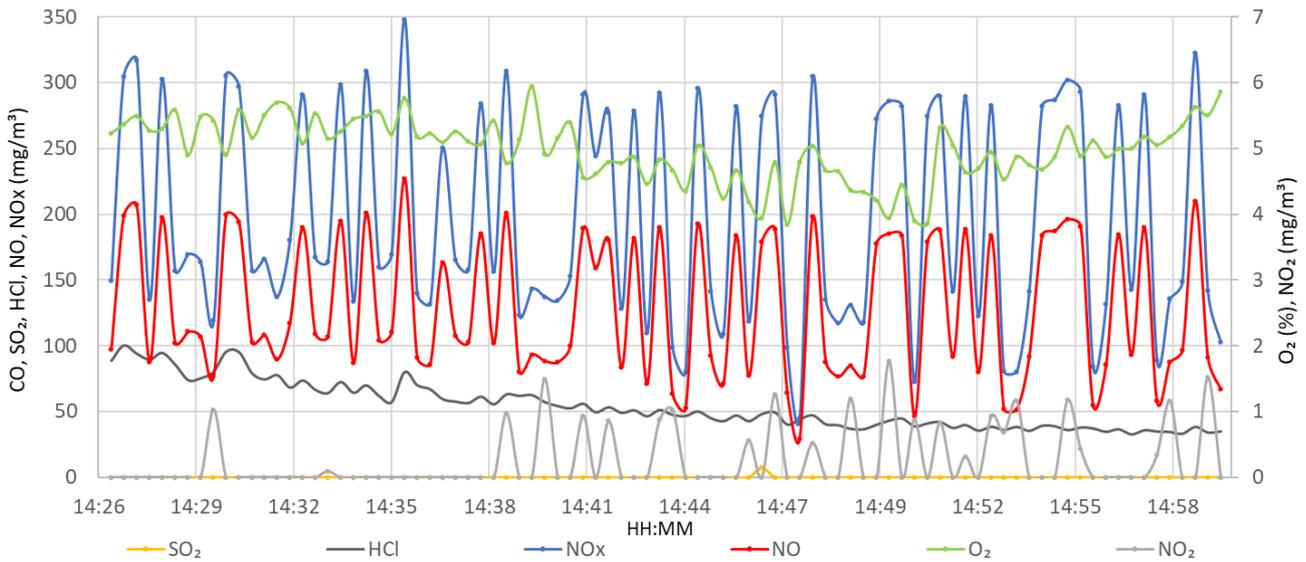
Fig. 4 8 MW boiler pollutant concentrations in combustion products

Table 2

Emission trends of 8 MW biofuel boiler

Flue gas component	Min. value	Max. value	Ave. value	STDEV
CO, mg/m^3	0.00	0.00	0.00	0.00
NO$_2$, mg/m^3	0.00	1.77	0.25	0.46
O$_2$, %	3.84	5.95	4.98	0.47
SO$_2$, mg/m^3	0.00	7.37	0.08	0.79
HCl, mg/m^3	32.56	100.58	54.21	18.18
NO, mg/m^3	29.69	227.24	128.16	54.27
NOx mg/m^3	45.51	348.32	196.72	83.20

It has been hypothesized that the instability of emissions is caused by certain combined mechanical and chemical processes in the furnace. For this reason, it was decided to conduct a more detailed measurement of emissions in experimental boiler model.

3.2. An experimental boiler model emission

Studies in an experimental boiler model have shown that emission concentrations in combustion products are also highly unstable (Fig. 5). The frequency of emission measurements every 1 second demonstrate repetitive peaks with increasing emissions. These changes were also observed when the boiler power output and flue gas temperature were stable.

Fig. 5 Experimental boiler model emissions during combustion of wood pellets

The oxygen concentration fluctuates periodically for 120 seconds. In the experimental model, the average O$_2$ concentration was higher compared to the industrial boiler and reached 7.5 %. This is due to scale factor. The frequency of changes in NO and NOx concentrations was approximately 20 seconds. This periodicity of concentration changes conforms with the periodicity of reciprocating grate movement. The measured NOx concentrations were lower compared to the industrial boiler and averaged 146 mg/m^3. This can be explained by differences in fuel quality shown in Table 1.

The average concentrations of NO$_2$, H$_2$S and SO$_2$ were low and did not exceed 7 mg/m^3, therefore the periodicity of changes in these compounds is not clear. However,

their highest concentration replicates changes in carbon monoxide and oxygen concentrations. The average concentrations of carbon monoxide were higher compared to industrial furnaces and amounted to 144 mg/m³.

This can be explained by the shorter residence time of combustion products at high temperatures due to the boiler model scaling factor. Due to the higher CO concentrations compared to the industrial boiler, it became clear that the periodicity of fluctuations in these emission concentrations has the opposite trend compared with O_2 concentration.

All organic solid biofuels contain a certain amount of nitrogen, sulfur and other substances. The higher this fraction, the higher concentrations of chemical compounds are formed from these elements. At relatively lower combustion temperatures (T<1200 °C), NOx is mainly formed from fuel nitrogen. Fuel NOx is estimated to account for more than 80 % of all nitrogen oxides in the combustion process [12].

In order to determine the dependence of the NOx and SO_2 emission fluctuations, emission measurements were performed by burning sunflower husk pellets with higher N and S contents (Fig. 6). Higher N and S levels (Table 1). may lead to higher NOx and SO_2 concentrations and allows to highlight them.
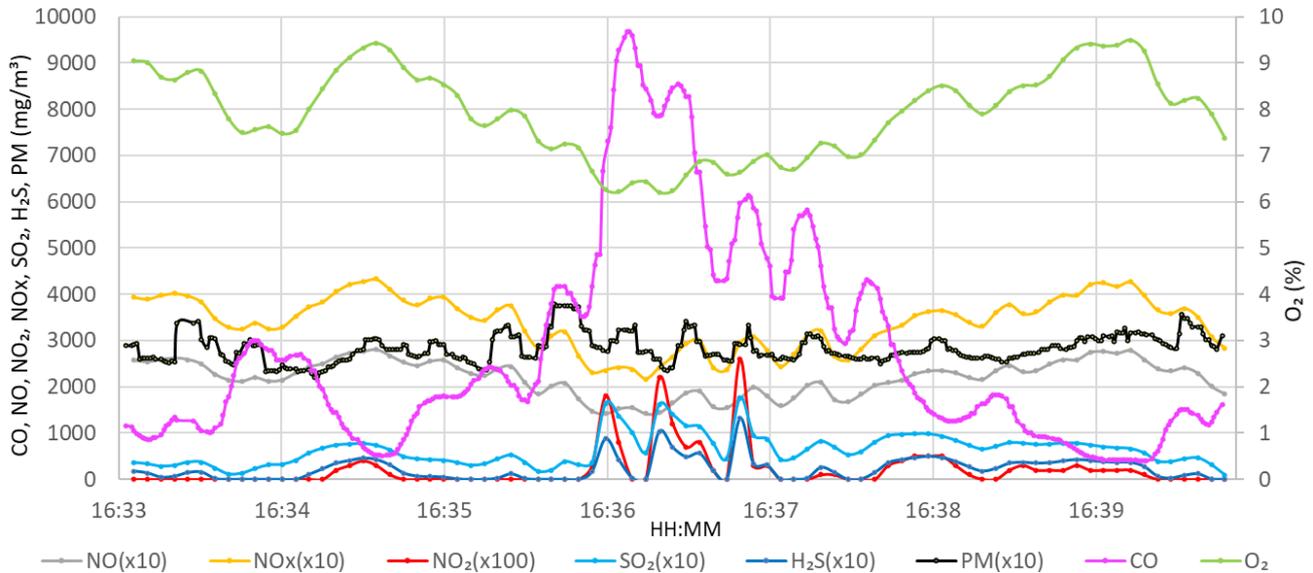
Fig. 6 Experimental boiler model emissions concentrations during combustion of sunflower pellets

The results of the experiment showed that by changing a fuel with higher sulfur and nitrogen content it leads to higher concentration of NOx and SO_2 emissions. The average values of nitrogen gaseous emissions increased in all cases. NO concentrations increased by 125 mg/m³, NO_2 by 2 mg/m³ and NOx by 193 mg/m³. Emissions of sulfur gas compounds also increased: SO_2 by 62 mg/m³ and H_2S by 16 mg/m³.

The measurements confirm that the concentrations of all components fluctuate periodically. The measurement of grate movement time shows correlation with the changes of concentrations of flue gas emissions. In both cases, the same 20-second periodicity was detected.

During this period, the grate performs the entire cycle of movement without stopping. The boiler load is related with the operation of reciprocating grate. The higher the load, the higher the speed or the more frequent the grate moves. Since the grate mechanism is based on a slider-crank mechanism, the grate movement can be described as a typical sinusoid (Fig. 7).

For comparison, the periodicity of industrial grate movement is also shown in Fig. 7. The character of the movement of the industrial grate is based on impulse. Industrial grate is driven back and forth by hydraulic cylinders with a certain power-dependent periodicity. The grate is pushed forward in small feeds (relative movements), then paused and moved forward again. When the final position of the grate is reached, the pulses acquire a negative meaning and the grate starts to move backwards. The movement of the industrial grate is proportional to the dimensions of the grate bars. In medium power boilers, the path length varies between 150 to 200 mm. The required industrial grate operation load is achieved by varying the pause time between movements.

On the experimental model the fluctuations of concentrations of flue gas components were much smoother, as shown in Fig. 6. Possibly due to the absence of sudden and impulsive movements compared with industrial boiler emissions (Fig. 4). Moreover, the path of movement of the experimental model grate is several times shorter and reaches 32 mm. This means that the influence of grate movement on the fuel layer and the change in combustion conditions can be reduced. Nevertheless, changes in the concentrations of particulate matter and gaseous pollutants are still visible. Particulate matter concentrations ranged from 143 to 256 mg/m³, with an average of 182 mg/m³.

It was observed that periodicity of the changes is the same compared with wood pellet burning experiments and reaches 20 seconds. This indicates that the movement of the grate has an effect on both the changes in the flue gas and the particulate matter emissions. Previous studies have shown that particulate matter concentrations are associated with incomplete combustion products such as CO. It has also been found an increase concentration of incomplete combustion products result in an increase in SO_2 emissions. On the other hand, a decrease in excess oxygen decreases NOx and H_2S concentrations.

It was also observed that the change profiles of H_2S, SO_2 and NO_2 are completely identical.

During the research performed in the 4 MW industrial boiler, the parameters of the operation of the combustion mechanisms (upper / lower grate movement with fuel supply) and oxygen with NOx concentrations were recorded. It was found that changes in NOx emissions and oxygen concentrations are only affected by the movement of the upper grate. Synchronous recording of this data allowed them to be combined (Fig. 8).

Periodic fuel feed into the furnace and the movement of the lower grate did not have any noticeable effect on the composition of the flue gas. The mechanical effect of the fuel feed mechanism on combustion processes is negligible. This can be explained by the fact that a new portion of fuel is fed into a drying zone where combustion and chemical emission processes are not yet taking place. The movement of the lower grate, which is moved by a separate mechanism, did not affect the changes in combustion emissions. This part mainly involves the final combustion of wood coke and ash cooling process, so the impact of this part of the grate on the composition of combustion products is minimal. For these reasons the lower grate movement and fuel feed characteristics is not shown for clarity in Fig. 8 for clarity reasons.

The mechanical movement of the upper grate, where the main combustion process already takes place, has a significant effect on NOx emissions and O_2 concentration. The periodicity of changes in NOx concentration emissions accurately replicates the movement of the grate. The average value of NOx was 266 mg/m^3 and the concentration ranged by 10-15 mg/m^3. The periodicity of changes in oxygen concentrations coincides with the NOx trend and also depends on the movement of the grate. The mean oxygen concentration was 6.22%, with a change of about 0.55 %.
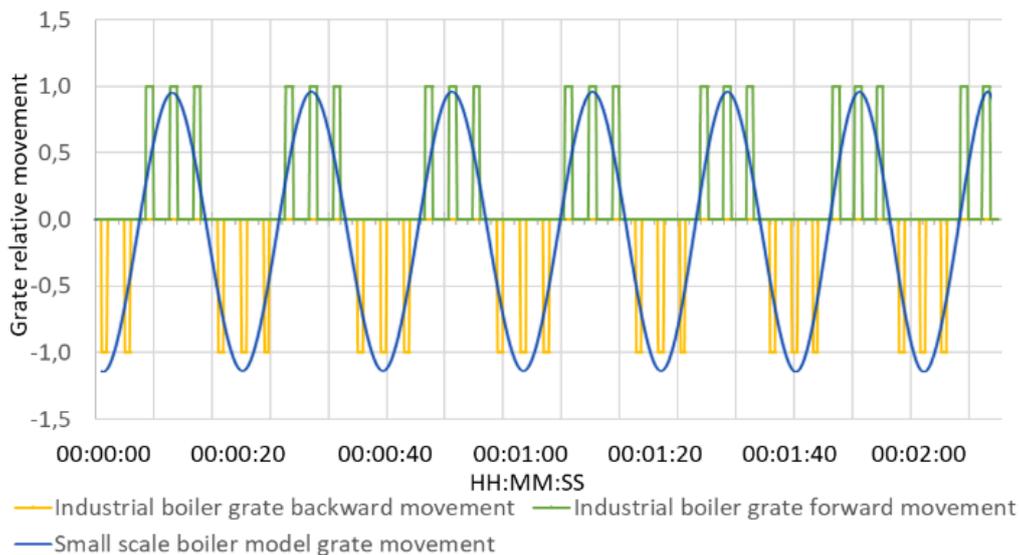
Fig. 7 Industrial and experimental boiler model grate motion characteristics
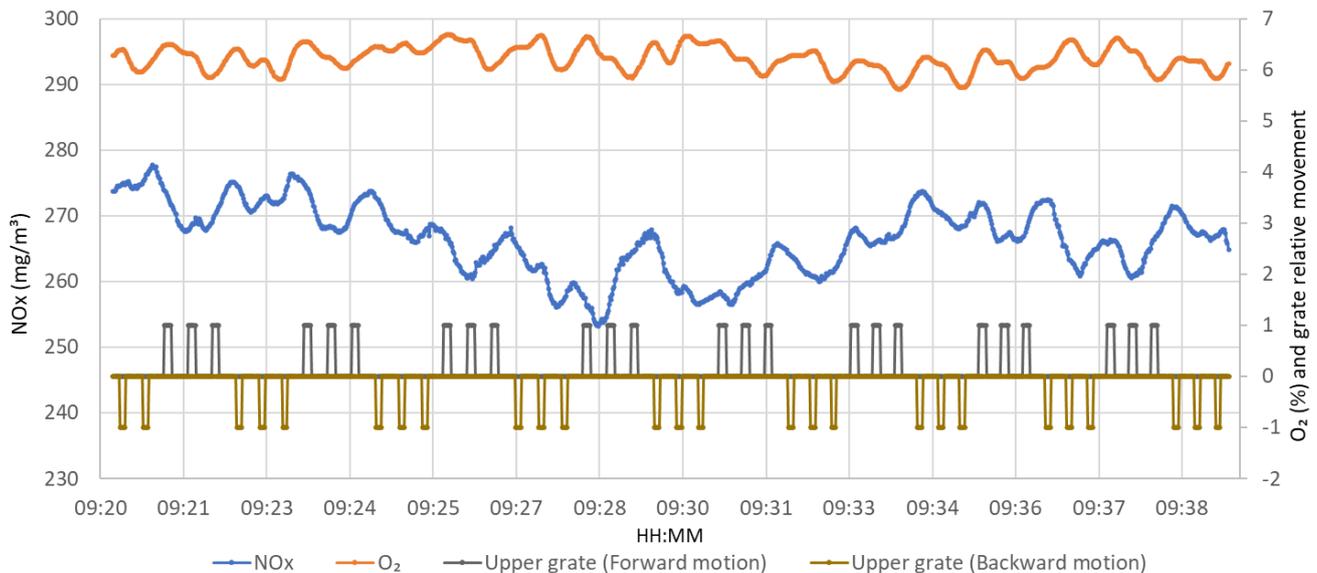
Fig. 8 The dependence of the 4 MW boiler flue gas emissions on the movement characteristics of the reciprocating grate

4. Results and discussion

Emissions from a boiler furnace can be divided into two parts. Some of the emissions are generated in the fuel bed, where the nitrogen and sulfur compounds in the fuel are oxidized in the fuel bed or a short distance above it. The other part of the emissions, including the release of volatile substances, is generated in the gas phase – in the greater

distance above fuel bed and in final combustion zone of the furnace. C. A. Bermudez et. al. [13] simulations of the distribution of C_6H_6, CH_4, CO and H_2 fractions in the midplane of the furnace showed that the largest changes in emissions occur right next to the fuel bed. For this reason, primary emission reduction measures must focus specifically on the processes taking place in this area.

The fuel bed of the reciprocating grate is characterized by stratification of the char and ash content with respect to the grate surface [13, 14]. As the grate moves forward, the certain fuel bed areas are pushed. Due to the stair arrangement of the grate, the fuel layer turns over. In this way, deeper pyrolysed fuel layers uncovers. The layer of pyrolysed fuel exposed by the movement of the grate can be effective medium in reducing emissions, e.g. for NOx reduction. Glarborg et al. found that NO formed when exposed to hydrocarbon radicals can be reduced to CHN or N_2 by surface reaction on carbon or soot surfaces [15].

SO_2 versus NOx have the opposite trend. SO_2 concentration increases with increasing concentration of incomplete combustion products and lack of oxygen. When the burning fuel layer is overturned the temperature of local areas in the fuel bed increases. A relationship between combustion temperature and SO_2 concentration has been observed by Obras-Loscertales et al. [16]. At temperatures above 925 ° C, SO_2 concentrations increase under fluidized bed furnace conditions. It should be noted that these temperatures are still insufficient for the formation of thermal NOx [14, 15].

In the gas phase, the concentration of incomplete combustion products has significant influence on emission concentrations. When the dried and partially pyrolysed fuel layer is opened, the amount of fuel ready for combustion increase significantly. Intensification of the combustion of gaseous pyrolysis products results a significant lack of oxygen above the fuel bed, as the amount of primary air supplied remains constant. Decreased oxygen levels drastically increase the concentration of hydrocarbons, carbon monoxide, and hydrogen.

Various publications indicate the influence of excess air on nitrogen oxide concentrations [12, 15]. When the $\lambda \ll 1$, competitive CO and NOx reactions occurs. In this way, a high efficiency reduction of NOx concentrations can be achieved. The dependence of SO_2 concentrations on excess oxygen has been little studied in the literature. The experimental results presented in Fig. 5 and Fig. 6 demonstrates that there is a relationship between CO and SO_2 concentrations. SO_2 concentrations were found to be indirectly proportional to CO concentrations and depends on the S quantity in the fuel.

Particulate matter is formed from two sources: the inorganic compounds of the fuel (ash) and the products of incomplete combustion (tar, carbon and soot) [17]. Relatively long flue gas path due to furnace vault, sufficient excess oxygen and a sufficiently high temperature, most of the organic particulate matter burn out before leaving the furnace. For this reason, the main mass of PM consists of inorganic compounds. This was confirmed by PM caloric measurements. During the movement of the grate, the surface of the fuel bed is mechanically disrupted. Elements such as Cl, S in the burning fuel bed together with Al, Si, K, Na, Ca, Mg, Fe, P, Ti and other elements generate aerosols and flying ash. These elements forming various compounds are dragged from the surface of the fuel bed by the primary air.

Particulate matter measurements performed on an experimental model (Fig. 6) demonstrate the correlation of PM concentrations with the periodicity of grate movement.

5. Conclusion

The movement of biofuel boiler reciprocating grate causes fluctuations of pollutant concentrations in short time intervals. NOx concentration can fluctuate from 8 to 60% depend on combustion condition – type of fuel, moving grates design, combustion air supply and lot of another factors, what must be investigate in detail. As the grate moves, the deeper layers of pyrolysed biofuel are opened and fluctuations of O_2 concentration can reach up to ± 0.5%, three times per minute (depends of grate moving regime). Because of generated fuel rich environment, at certain moments, the lack of oxygen occurs. Concentrations of CO and other hydrocarbons are formed resulting a reducing environment for the emissions. Due to competitive reactions between CO and NOx, a significant reduction of NOx concentrations in flue gas can be achieved. At the same time, particulate matter emissions are increasing by 10-20% due to increased hydrocarbon and soot emissions along with the drag of coke and ash by the primary air stream. The decrease in excess oxygen during the movement of the grate causes a jump in the increase of SO_2 and H_2S concentrations.

In order to reduce emissions further, reciprocating grate must move as smoothly as possible, giving priority to the continuous movement of the grating over a grate with pulsed movement properties.

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GRATE-FIRING BOILERS GRATE MOVEMENT IMPACT ONTO NOx, SO$_2$ EMISSIONS

S u m m a r y

Measurements of pollutant concentrations in the flue gases of a biofuel boiler show that pollutants concentrations fluctuate by 10-100% and more at short time intervals. Large fluctuations in concentrations hinder the effective application of pollution reduction measures. During the research, flue gas composition measurements were performed in 4 MW, 8 MW industrial biofuel boilers and 20 kW experimental model. The results of the research showed that the change of CO, NO, NO$_2$, SO$_2$, H$_2$S, O$_2$ and particulate matter concentrations is related to the periodicity of the boiler grate movement. During the movement of the grate, the surface of the fuel bed is mechanically disrupted. The different composition of the fuel layers is mixed and this affects the changes in the concentration of combustion products. The clarity of the concentration fluctuations depends on the emissions, the type of fuel and the combustion parameters.