KAUNAS UNIVERSITY OF TECHNOLOGY

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REDUCTION OF NITROGEN AND SULFUR COMPOUND EMISSIONS IN BIOFUEL BOILERS USING COMBINED METHODS

Summary of Doctoral Dissertation
Technological Sciences, Energetics and Power Engineering (T 006)

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SUMMARY

INTRODUCTION

Tightening emission standards and growing energy needs pose challenges to the regulation of gaseous pollutants in combustion products. Alternative to wood, biofuels with higher sulfur and nitrogen content, which are the main sources of SO_2 and NOx emissions, are being burned increasingly. The growing global focus on renewable energy and the reduction of CO_2 emissions has led to an increase in research on this topic. Nevertheless, they do not examine in sufficient detail the emissions of the main pollutants emitted during the incineration of agricultural and industrial waste biomass – sulfur (SO_2, SO_3, H_2S) and nitrogen (NO, NO_2, N_2O, HCN, NH_3) compounds and emission reduction technologies in industrial reciprocating grate biofuel boilers. Boilers of this type usually produce thermal energy for the users of district heating network and various industrial and economic entities, hence they are located in or near a residential area, which are sensitive to atmospheric pollution. Studies are often based on theoretical assessments or results obtained on test benches, where the combustion conditions do not always correspond to the actual combustion conditions in industrial-size boilers. Scientific publications usually examine separate applications of reduction methods rather than combined ones, acting on several groups of pollutants, although the use of biomass can exceed both SO_2 and NOx standards.

Object of investigation

The reduction of sulfur and nitrogen gaseous compounds in the flue gas of a medium combustion plant with a moving grate.

The aim of the work

To investigate the impact of combined primary and secondary measures on the reduction of nitrogen and sulfur emissions during the combustion of wood chips and agro-waste.

The objectives of the thesis

1. To investigate the reasons for fluctuations of pollutant concentration in biofuel boilers and prepare a methodology of the measurements;
2. To investigate the effect of a combination of selective non-catalytic reagents and incomplete combustion products on the emissions of NO, NO_2, N_2O, NH_3, HCN, SO_2, SO_3, and H_2S;
3. To investigate the effect of combined solid reagents and flue gas recirculation on the emissions of nitrogen and sulfur gaseous compounds;
4. To investigate the effect of flue gas recirculation and partial combustion products on the emissions of nitrogen and sulfur gaseous compounds;
5. To investigate the effect of flue gas recirculation and solid reagents on emission concentrations.

Scientific novelty of the work

1. The combined effect of different emission reduction methods on gaseous pollutant emissions from the combustion of biofuels in moving grate boilers has been determined;
2. Flue gas recirculation and partial combustion of biofuels reduce the emissions of certain pollutants but increase the emissions of other pollutants, thus a combination and optimization of different emission reduction measures is required depending on the N and S content of the fuel and the conditions of application of the measures.

Practical significance of the work

1. Based on the results of experimental research, a methodology for calculating the concentrations of NOx and SO_2 has been developed, which allows for the optimal selection of emission reduction measures, namely, partial combustion, flue gas recirculation, reagent injection into moving grate biofuel boilers to reduce NOx and SO_2 emissions and preliminary assessment of their effectiveness;
2. A combined NOx, SO_2, and H_2S emission reduction system for industrial firetube boilers was developed, tested, and installed in boiler houses in the Netherlands, Czech Republic, Finland and Estonia;
3. The research on the dependence of emissions on the movement of the grate showed the directions for the reduction of emissions by optimizing the grate movement and fuel supply systems.

Defensive propositions of the dissertation:

1. Fluctuations in the concentrations of NO, NO_2, SO_2, SO_3, H_2S, O_2, CO, and KD are caused by the effect of grate movement on the fuel bed in the pyrolysis zone. The content of S and N in the biomass determines the levels of concentrations and the amplitudes of their fluctuations;
2. During selective non-catalytic reactions, the $(NH_2)_2CO$ reagent reduces not only the concentrations of NO and NO_2, but also those of SO_2 and H_2S in biofuel combustion products. In the case of combustion with CO generation, low NOx concentrations are achieved. Supplemental urea supply has little effect on NOx;
3. Recirculation of combustion products together with primary air reduces the concentrations of NO, NO_2, NH_3, SO_3, and H_2S, but increases the concentrations of SO_2, HCN, and N_2O. The intensity of these changes depends on the completeness of fuel combustion, i.e. on the concentration of CO in the combustion products;
4. The influence of oxygen on N and S gaseous compounds is lesser than that of partial combustion in the case of CO generation. The effect of incomplete combustion on the concentrations of NOx and SO_2 is the opposite;
5. The formation of SO_2, SO_3, and H_2S takes place mainly in the combustion zone of biofuel pyrolysis gaseous products and the effect of CaO on the reduction of emissions of these sulfur compounds must be directed to this zone.

METHODOLOGY

The research was carried out in stands and boilers of various capacities and constructions. The composition of emissions during fuel combustion and the concentration of pollutants depends on fuel properties, combustion temperature, and the technological characteristics of the furnace, therefore this study performed measurements in different industrial boilers and combustion stands. Measurements of industrial emissions were performed in 4 MW, 5 MW, 8 MW, 10 MW and 12 MW biofuel boilers. These boilers differ in the size of the furnace and the arrangement of air and flue gas recirculation in the furnace. The 4 MW boiler is equipped with a secondary air supply above the fuel layer, while the 5 MW, 8 MW, 10 MW, and 12 MW are furnaces with flue gas recirculation.

A total of three experimental stands were used for research: 1) a domestic wood pellet boiler KSM-175-13-U (manufacturer Kalvis) 2) an experimental stand of combustion research laboratory at Kaunas University of Technology (KTU) 3) an experimental stand of Enerstena's R&D laboratory. Experimental stands are characterized by combustion conditions typical of industrial boilers, i.e., combustion on a movable grate, high temperatures, etc. The KTU boiler-stand has a combustion chamber simulating an industrial boiler furnace but the path of combustion products at high temperatures is not long, combustion products remain in this part only for up to 0.4 s. As a result, another stand at the Enerstena Research Center was designed and manufactured. The high-temperature section integrated in the stand is a reactor to which various reagents for reducing emissions can be supplied. The reactor allows the adiabatic conditions required for selective non-catalytic reactions to be maintained for a sufficiently long time (4.8 s). The openings in the reactor and the furnace are designed for measuring the composition of combustion products and for supplying air, recirculated flue gas, or reagents to different places of the furnace.

Experimental stands have all the technological elements to create the combustion conditions typical of industrial mobile grate boilers, i.e., a two-stage combustion chamber with a temperature of 750°C to 1100°C, separately controlled primary and secondary air flows, maintained stable pressure in the furnace, as well as adjustable grate motion speed and fuel supply. The efficiency of fuel supply, grate movement, and traction fans are controlled by frequency converters. The atmosphere pressure in the furnace is controlled automatically and does not depend on the amount of air and flue gas recirculation supplied to the combustion chamber. This makes it possible to eliminate the influence of air intake on the combustion product on the composition of combustion products under different combustion modes. The schematic diagram of both stands is shown in Figure 1.1.

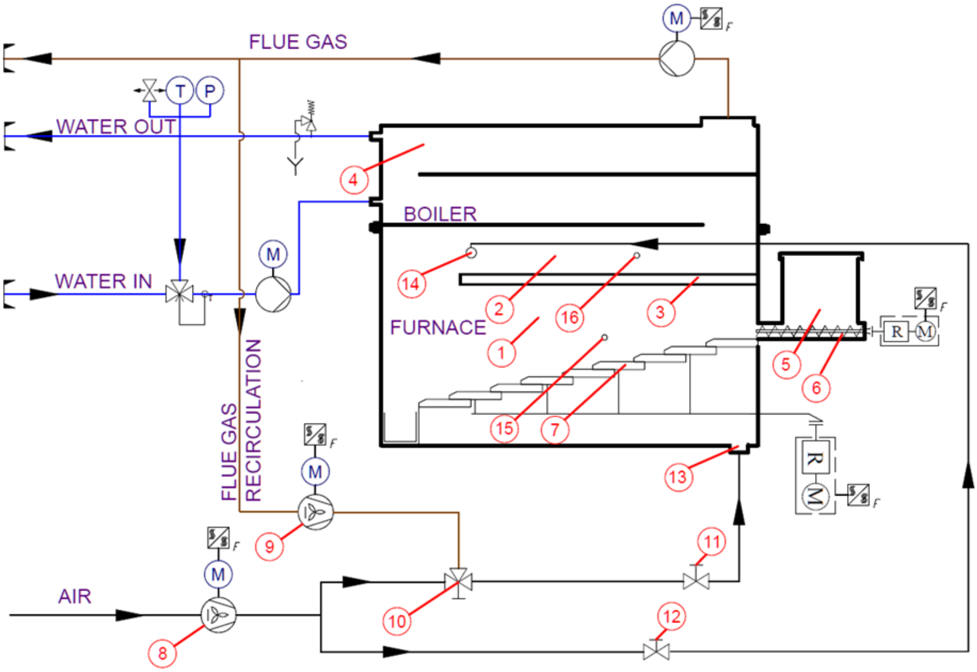

Fig. 1.1. The functional scheme of experimental stand: 1–primary combustion zone, 2–secondary combustion zone, 3–chamotte arc, 4–water heating boiler, 5–pellet bunker, 6–pellet feeding screw conveyor, 7–moving grate, 8–combustion air fan, 9–flue gas recirculation (FGR) fan, 10–primary air/flue gas mixing valve, 11–primary airflow control valve, 12–secondary airflow control valve, 13–primary air inlet, 14–secondary air inlet, 15–primary combustion zone temperature measurement, 16–secondary combustion zone temperature measurement

Industrial boilers are equipped with a vault at the beginning of the furnace where the fuel is supplied due to wet fuel combustion. This allows the reverse course of the flame to be maintained, helping to dry the fuel used in industrial boilers. Conversely, in experimental stands, due to relatively dry fuel, the vault is mounted at the end of the furnace.

A small portion of the experiment was performed in the domestic boiler KSM-175-13-U. The boiler was selected to study the concentrations of pollutants in the combustion of various types of biofuels in low-temperature, water-cooled furnaces and to investigate the possible applications of these emission reduction measures.

Fuels

Fuels of different origins were used in the experimental research: agricultural, furniture manufacturing, animal waste, and wood biomass. These fuels have different chemical compositions and combustion properties. The use of different fuels allows to assess the dependence of emissions on fuel composition and to identify clearer trends. The physical and chemical characteristics of the fuels are given in Table 1.1.

Table 1.1. Typical characteristics of wood pellets

Characteristic	Moisture content, %	Ash content, %	Lower calorific value, MJ / kg	N, %	S, %
Wood pellets	7.0	0.2	16.4	0.15	0.01
Wood chips	48.5	2.9	8.3	0.41	0.01
Furniture manufacturer pr. waste pellets	4.0	0.4	18.2	3.14	0.01
Sunflower hull pellets	8.6	2.9	16.0	0.51	0.08
Peat pellets	8.2	3.0	18.6	1.13	0.04
Oat hull pellets	11.4	3.4	15.3	1.13	0.15
Bone meal	2.8	22.1	17.1	9.68	0.59

Wood pellets and wood chips were selected as the cleanest biomass species containing the least quantities N and S. Wood pellets were used in experimental stands to set base emission values for comparison with other biomass species. Furniture production waste pellets made from particle board waste have high nitrogen contents, therefore, due to the generated high NOx values, they were used to investigate the feasibility of NOx reduction measures.

Sunflower husk pellets and peat pellets have been used in studies on higher S levels to investigate the effectiveness of sulfur emission reduction measures. Chemical composition studies show that oat husks contain higher amounts of nitrogen, sulfur, potassium, and phosphorus. Potassium and phosphorus lower the ash softening temperature, while nitrogen and sulfur increase the concentrations of NOx and SO_2 in the flue gas. Meat bone meal has a high calorific value and is rich in natural amounts of sulfur and nitrogen in the amino acids, which are the main source of NOx and SO_2 emissions during combustion.

Measuring instruments

During the experimental studies, emissions were measured with four analyzers operating on different measurement principles. The concentrations of gaseous combustion products were measured with the Gasmet DX4000, MRU Vario luxx, and Siemens Ultramat 23 analyzers, and particulate matter concentrations were measured with the Afriso STM 225. The Gasmet DX4000 analyzer operates on the Fourier Transform Infrared Spectrometer (FTIR) principle. The MRU Copper luxx analyzer measures electrochemical cells. The continuously operating Siemens Ultramat 23 analyzer measures the composition of flue gas with a non-dispersive infrared (NDIR) element. In the particulate matter analyzer, the concentrations are evaluated with an optical device that operates on the scattered light measurement principle. All of these analyzers are equipped with heated hoses, probes and flue gas preparation units. The exception is the Afriso STM 225 analyzer as it does not have a flue gas preparation unit.

Optical measuring instruments were used to monitor the processes in the furnace. Spectral characteristics of biofuel flame emissions were measured with the 200–1100 nm Ocean Optics Jaz and 200–900 nm Ocean Optics Flame spectrometers. The frequency of flame luminosity fluctuations was measured with visual and infrared sensors OPT101 by recording signal changes with the microcontroller NUCLEO-F746ZG. Temperatures in the overhead and final combustion zones were registered with K-type thermocouples by recording readings with the PicoLogo TC-08 recorder.

Processing and analysis of results

The results of the measurements are given for dry flue gas, converted to a concentration of 6% O_2. Studies have shown that periodic fluctuations in the combustion product concentration occur, so a special measurement data processing methodology was developed in which the obtained results were sorted according to O_2 or CO concentrations and the data are averaged. Therefore, the data in the figures are averages of tens or hundreds of measurement results. This technique allowed the detection of even small changes in flue gas composition smaller than the amplitudes of concentration fluctuations.

For the experiments with flue gas recirculation, a calculation methodology has been developed, which allows to estimate what part of the boiler flue gas is returned back to the furnace. By adjusting the proportions of boiler flue gas and combustion air, the amount of flue gas recirculation was controlled by the oxygen concentration in the mixture. Flue gas recirculation ranges from 0% to 52%.

Generalization of the experiments

A summary of boilers, name abbreviations, fuels and used emission reduction measures is presented in Table 1.2.

Table 1.2. A summary of boilers, measurements and used methods

Boiler	Abbre-viation	Power	Fuel*	Measurements				Methods of emission reduction				
				Optical	Spectral	Tempe-rature	Emissions	Excess air	Flue gas recircu-lation	NH_3	$(NH_2)_2CO$	CaO
Experimental stand of Kaunas University of Technology	KTU-TS	20 kW	W.P., M.B.M., F.P.W., S.H.P., P.P., O.H.P.	✓	✓	✓	✓	✓	✓	✓		✓
Experimental stand of Enerstena R&D laboratory	EN-TS	20 kW	W.P., S.H.P.			✓	✓	✓	✓		✓	✓
Domestic wood pellets boiler of KUT	KTU-BK	13 kW	F.P.W.				✓	✓				
Industrial boiler (4 MW)	PK-4	4 MW	W.C.			✓	✓				✓	
Industrial boiler (5 MW)	PK-5	5 MW	W.C.				✓	✓			✓	
Industrial boiler (8 MW)	PK-8	8 MW	W.C.		✓		✓				✓	
Industrial boiler (10 MW)	PK-10	10 MW	W.C.			✓	✓				✓	
Industrial boiler (12 MW)	PK-12	12 MW	W.C.				✓	✓				

*W.P.–Wood pellets; M.B.M.–Meat bone meal; F.P.W.–Furniture production wastes; S.H.P.–Sunflower hull pellets; P.P.–Peat pellets; O.H.P.–Oat hull pellets; W.C.–Wood chips.

RESULTS

Investigations of the causes of fluctuations in the composition of combustion products

The author has conducted research in industrial 4 MW and 8 MW boilers and a 20 kW experimental stand, the results of which have been published in an international peer-reviewed journal. Emission measurements in an industrial 8 MW boiler have shown that pollutant concentrations are highly unstable over time, even when the boiler operates in constant power output. Fluctuations in concentrations make it difficult to accurately dose selective reagents, as their amount must depend on the NOx concentration. Moreover, these fluctuations in emissions may lead to misinterpretation of the data. For this reason, studies have been conducted in an experimental stand to determine the causes of these fluctuations.

Fluctuations in O_2, CO, NO, NO_2, NOx, SO_2, H_2S, and particulate matter concentrations measured during heating of wood and sunflower pellets were correlated with the grate movement periodicity of 20 seconds. The results of measurements of sunflower husk combustion emissions (Fig. 1.2) showed that fuels containing more nitrogen and sulfur increase both the averages of emissions and the amplitudes of fluctuations, highlighting the fluctuations of emissions. The concentrations of NO increased by 125 mg/m^3, NO_2 increased by 2 mg/m^3 and NOx by 193 mg/m^3 compared to wood pellet emissions. The concentrations of sulfur compounds also increased: SO_2 by 62 mg/m^3 and H_2S by 16 mg/m^3.

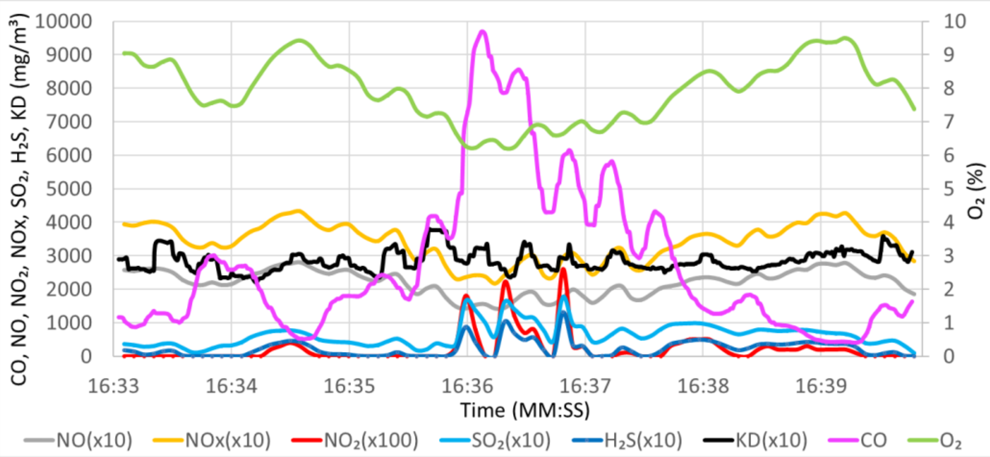

Fig. 1.2. Fluctuations of Kaunas University of Technology experimental stand flue gas emissions during combustion of sunflower hull pellets

Particulate emissions (KD) also showed clear periodic fluctuations, especially between 16:35 and 16:37. Particulate matter concentrations ranged from 221 mg/m^3 to 379 mg/m^3 with an average of 283 mg/m^3. The periodicity of the particulate concentrations coincided with the concentrations of the gaseous compounds and was 20 seconds. The same period was determined by measuring the changes in the intensity and temperature of the flame glow above the fuel layer. In cooperation with the Institute of Metrology of Kaunas University of Technology, an optical device for recording light signal pulsations (fluctuations) was developed, which was used to scan the frequencies of flame fluctuations in the experimental stand of KTU. Measurements of flame glow pulsations were performed at a distance of 100 mm above the fuel layer. The spectrogram data show that the intensity of the light signals recorded at the beginning and end of the grate is very low. The most pronounced periodically recurring flame glow is seen in the middle of the grate, where volatile substances burn in the flame. The periodicity of the measured signals coincided with the previously performed periodicity of emission fluctuations and the period of grate movement, i.e., full forward/reverse cycle of the grate.

Temperature measurements along the grate in UAB Enerstena's experimental stand were performed, linking them with changes in O_2, CO, NO, NO_2, SO_2, and H_2S emissions in the boiler flue gas. K-type thermocouples without a protective cover for fast temperature measurement were used for the measurements. Thermocouples are arranged at equal (100 mm) distance from the beginning to the end of the grate. They are installed at a distance of 30 mm from the furnace wall and retracted at the same distance above the fuel layer. The observed average temperature fluctuation averaged by 14°C. Determined periodicity is evidently related to the movement of the grate. This period clearly coincided with fluctuations in the concentrations of O_2, NO, and SO_2 emissions measured at the same time.

In order to determine whether the same regularities of emission fluctuations can be detected in industrial furnaces, research was performed in a 4 MW boiler. During the study, O_2 and NOx emission concentrations were measured by recording the movement of the grate. NOx and O_2 concentrations were found to be dependent on the movement of the grate (Fig. 1.3).

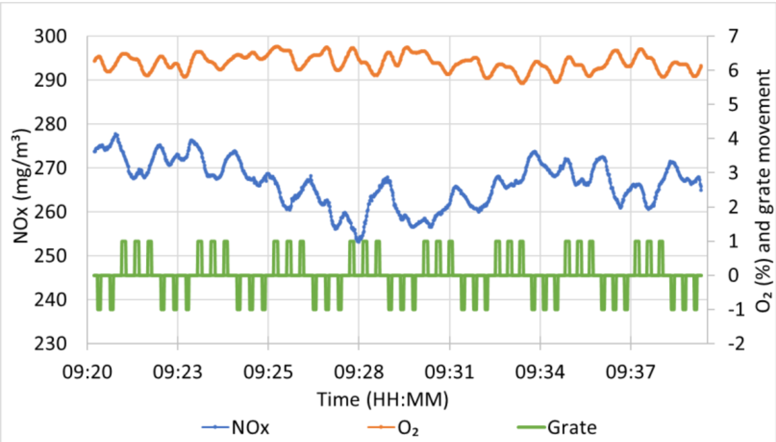

Fig. 1.3. The dependence of flue gas emissions on grate movement in a 4 MW power boiler during combustion of wood chips

The periodicity of changes in NOx concentrations accurately replicates the frequency of grate movement. The average NOx emissions were 266 mg/m^3, with changes in concentrations ranging from 10 to 15 mg/m^3. The periodicity of changes in oxygen concentrations was in line with NOx trends and also depended on grate movement. The mean O_2 concentration was 6.2% with a change of approximately 0.6%.

The effect of grate movement on O_2, CO, and NOx emissions can be observed in several publications [71–75]. Zhang et al. [71] performed measurements and simulations of district heating 320 kW wood chip boiler emissions, which showed that the levels of O_2, CO_2, and CO concentrations fluctuate particularly over an hour. Emission instabilities have also been observed by Sippula et al. [72]. Fluctuations in emission concentrations in the 500 kW pellet boiler were clearly visible when burning lower quality fuel, i.e., bark. The nature of emission fluctuations has also been observed by Leskinen et al. [73]. These authors attribute the instabilities of oxygen and partial combustion product emissions to the mechanical effects of fuel supply and grate movement, but do not explain the process.

The reasons for these fluctuations can be explained by two mechanisms. First of all, the movement of the grate causes intensive gasification, which releases large amounts of incomplete combustion products [72]. Glarborg et al. [10] found that the formed NO, exposed to hydrocarbon radicals, can be reduced to CHN or N_2 due to a surface reaction on carbon or soot surfaces. Another reason is related to the uneven covering of the primary air supply slots in the grate. As the grate moves, some of the fuel is pushed away from the air vents in the grate, thus distorting the local excess air [75]. These openings also contribute to particulate concentrations. Particulate matter is formed in the combustible fuel layer by reacting Cl, and S with Al, Si, K, Na, Ca, Mg, Fe, P, and Ti elements to form aerosols and fly ash. As the grate moves, the burning fuel layer is mechanically destroyed. Particulates are separated from the primary air in the fuel bed and further taken out with the combustion products.

The performed studies allowed to understand the reasons for the fluctuations in the composition of combustion products and these processes were taken into account while processing the data of experimental studies.

Combined influence of liquid reagents and CO on flue gas composition

Previous studies of selective non-catalytic measures while burning waste from the furniture manufacturing industry have shown that NOx emissions can be reduced by up to 68%, but no other emissions have been investigated during these experiments. For this reason, more detailed tests were performed on an experimental stand to determine the effect of a 32.5% urea $(NH_2)_2CO$ solution on the concentrations of CO, SO_2, H_2S, NOx, NO, and NO_2. Sunflower hull pellets were burned during the study. Urea content is given as a recalculated percentage of fuel mass (% f.m). The results of the measurements are shown in Figure 1.4.

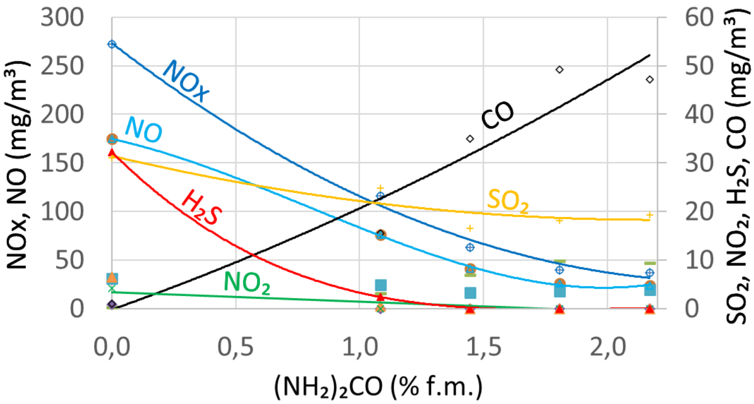

Fig. 1.4. The dependence of flue gas emissions on urea quantity in Enerstena's experimental stand during combustion of sunflower hull pellets

By injecting 1.08% urea from fuel mass into the reactor, NOx concentrations decreased from 272 mg/m^3 to 116 mg/m^3, the NO concentration decreased from 175 mg/m^3 to 76 mg/m^3, and the NO_2 concentration decreased from 4.2 mg/m^3 to 0 mg/m^3. The SO_2 concentration decreased from 31 mg/m^3 to 25 mg/m^3 and the H_2S concentration decreased from 31 mg/m^3 to 2.5 mg/m^3. Increasing the reagent level to 2.2% increases the changes in emissions, and the NO_2 and H_2S concentrations disappear. Further comparison of different concentrations of urea solutions shows that a higher concentration of the solution leads to a higher reduction efficiency of nitrogen and sulfur compounds.

The effect of increasing the CO concentration is observed during the supply of urea solution. The supply of 1.08% urea by weight of fuel increased CO from 0 mg/m^3 to 16 mg/m^3. An increase in CO concentration was also observed in an industrial 4 MW boiler equipped with a selective non-catalytic NOx reduction system (Fig. 1.5).

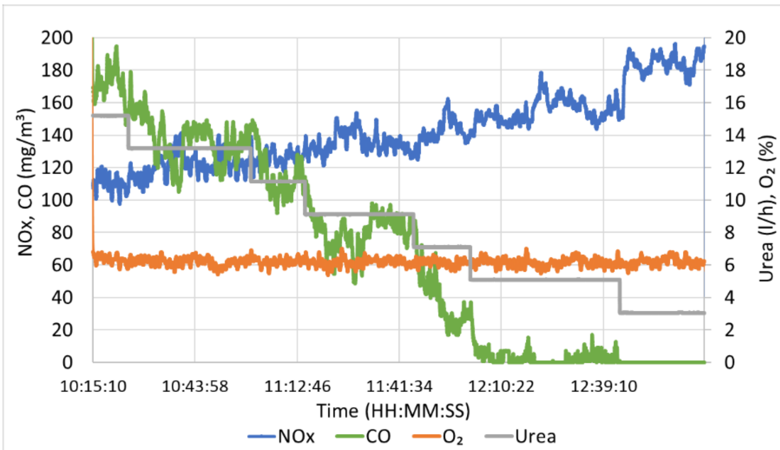

Fig. 1.5. The dependence of flue gas emissions of a 4 MW industrial boiler and the supply of urea during combustion of wood chips

Stable oxygen concentrations in the flue gas indicate that the concentration of carbon monoxide is not caused by a lack of air. An increase in CO concentrations from 0 mg/m^3 to an average of 170 mg/m^3 correlates with the amount of urea supplied. The higher its content, the higher concentrations of CO can be expected. In the presence of excess reagent, incomplete decomposition reactions of urea occur and CO is partially formed instead of CO_2. Excess reagent also determines the concentration of NH_3 in the flue gas. Studies in a 5 MW industrial boiler have also shown that the concentration of NH_3 in the flue gas depends on both the amount of reagent and the concentration of the solution (Fig. 1.6).

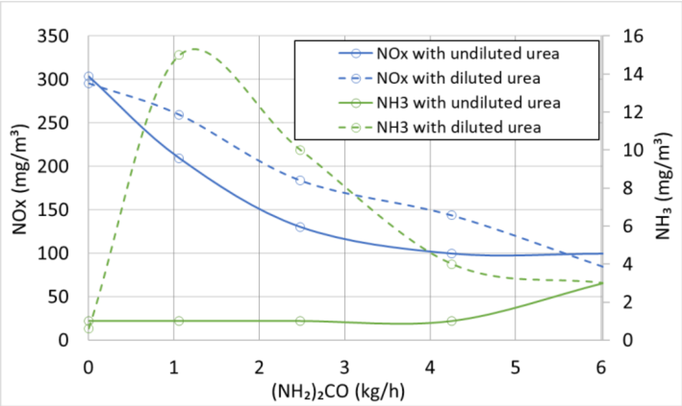

Fig. 1.6. The dependence of flue gas emissions of a 5 MW industrial boiler on the supply of the urea and its dilution during combustion of wood chips

Solutions of five different concentrations were supplied during the experiment. The proportion of urea in a diluted and undiluted solution was kept equivalent, only the part of water changed. The results show that with excess supply of the undiluted solution, when the reagent content reached 6.0 kg/h, the NH_3 concentration in the flue gas increased from 1 mg/m^3 to 3 mg/m^3. Meanwhile, a maximum NH_3 concentration of 15 mg/m^3 was reached at the maximum dilution of the reagent when urea quantity reached 1.1 kg/h. This difference can be explained by the local decrease in temperature due to the influence of water and the size of the droplets. The higher the water content in the solution, the longer it takes for the water content to evaporate. Just after this process pure $(NH_2)_2CO$ can decompose into NH_3 and HCN. The optimum temperature is required to accelerate evaporation.

The optimum temperature in the final combustion zone for effective selective non-catalytic reactions was determined in a 10 MW industrial boiler (Fig. 1.7). During the experiments, different reagents, urea and ammonia solutions were supplied at the beginning of minute 4 and supplied for 5 minutes at temperatures between 950°C and 1100°C.

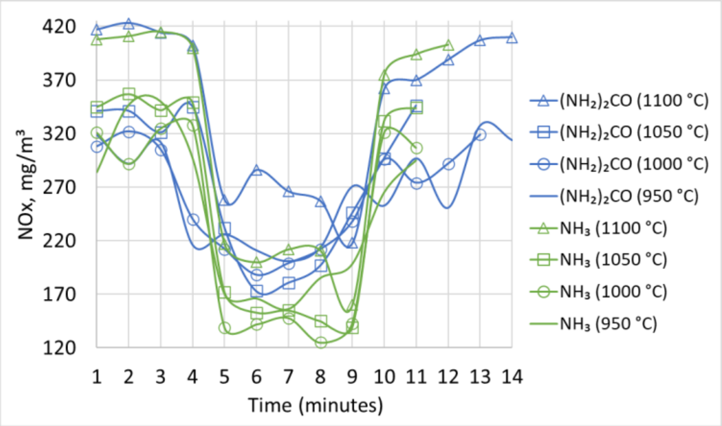

Fig. 1.7. The dependence of flue gas emissions of the10 MW industrial boiler on the temperature at the injection site and the type of solution during combustion of wood chips. Noted solutions were injected at minutes 4–9 of the experiment

The obtained results show that the efficiency of selective non-catalytic reactions depends on both the reaction temperature and the type of reagent. The highest NOx reduction efficiency was achieved at a flue gas temperature of 1050°C. The optimum temperature did not depend on the type of reagent. At lower temperatures, the rate of selective reactions slows down, and at too high temperatures the NH_3 and $(NH_2)_2CO$ reagents begin to dissociate into atomic nitrogen, which is oxidized to NO at high temperatures.

Experimental research described above were used to develop a unique selective nitrogen oxide emission reduction system implemented in industrial medium power biofuel boilers.

Concentrations of incomplete combustion products and other compounds are directly dependent on excess oxygen. Most authors' publications simply examine the influence of oxygen on nitrogen oxide emissions, which is why more detailed studies have been carried out to measure the change in sulfur and nitrogen gas compounds due to excess air. Biomass and waste of various origins were selected for research:

1) biomass of plant origin, i.e., wood pellets;
2) biomass of animal origin, i.e., meat bone meal;
3) agro-waste biomass i.e., sunflower hull pellets;
4) industrial furniture production waste, i.e., laminated chipboard.

All fuels were burned in an experimental stand. During the studies, the amount of secondary air gradually changed, thus reducing the oxygen concentration in the flue gas (Fig. 1.8).

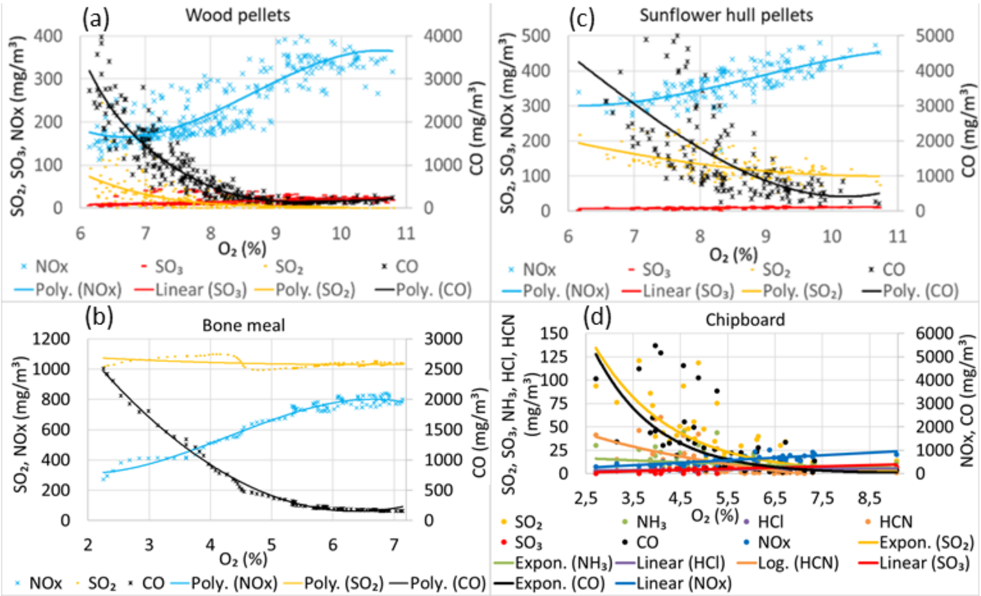

Fig. 1.8. The dependence of flue gas emissions of Kaunas University of Technology experimental stand (a, b, c) and domestic boiler (d) on O_2 concentration in flue gas

When burning wood pellets (Fig. 1.8 a) with sufficient excess of O_2, the concentrations of NOx and SO_2 were the lowest compared to other fuels and amounted to 360 mg/m^3 and 0 mg/m^3, respectively. Reducing the oxygen concentration in the flue gas from 11% to 6% increased the concentrations of CO (from 250 mg/m^3 to 3200 mg/m^3) and SO_2 (from 0 mg/m^3 to 75 mg/m^3). The concentrations of NOx and SO_3 demonstrate the opposite dependence on O_2. NOx decreased from 360 mg/m^3 to 160 mg/m^3 and SO_3 from 25 mg/m^3 to 5 mg/m^3. When burning bone meal (Fig. 1.8 b), CO emissions were much lower. Similar (2500 mg/m^3) CO emissions were achieved at an O_2 concentration of 2.2%. SO_2 emissions, meanwhile, increased slightly from an average of 1050 mg/m^3 to 1080 mg/m^3. High SO_2 concentrations were due to high (< 1.0%) sulfur content in the fuel. Reducing O_2 concentrations from 7.2% to 2.2% reduced NOx emissions from 800 mg/m^3 to 300 mg/m^3. Although the calculated SO_2 concentrations were expected to be around 1600 mg/m^3, a large part of the sulfur remained bound in the ash in the form of sulphates, due to the specific composition of bone meal. The combustion of sunflower husk pellets (Fig. 1.8 c) and reduction of excess air increased the CO concentration from 500 mg/m^3 to 4300 mg/m^3, SO_2 increased from 100 mg/m^3 to 200 mg/m^3. NOx concentrations decreased from 500 mg/m^3 to 300 mg/m^3 and SO_3 slightly decreased from 10 mg/m^3 to 7 mg/m^3. Chipboard NOx emissions (Fig. 1.8 d) were three times higher compared to wood pellets. Reducing O_2 from 9.5% to 3.2% reduced NOx emissions from 1000 mg/m^3 to 300 mg/m^3 and SO_3 from 10 mg/m^3 to 0 mg/m^3. When CO emissions increased from 70 mg/m^3 to 5200 mg/m^3 and SO_2 increased from 20 to 130 mg/m^3.

The influence of excess air O_2 concentration on chipboards, painted wood fiber board, and plywood combustion emissions were also determined in the experimental stand. Emissions of plywood were compared with the measurements made in a domestic wood pellets boiler. The domestic boiler is dominated by cold, water-cooled surfaces and a single-stage air supply, so even with a large excess of air, the measured CO emissions were 35–40 times higher than those of the experimental stand.

For a comparison of emissions, additional studies of the influence of excess air were performed in 5 MW and 12 MW industrial boilers (Fig. 1.9).

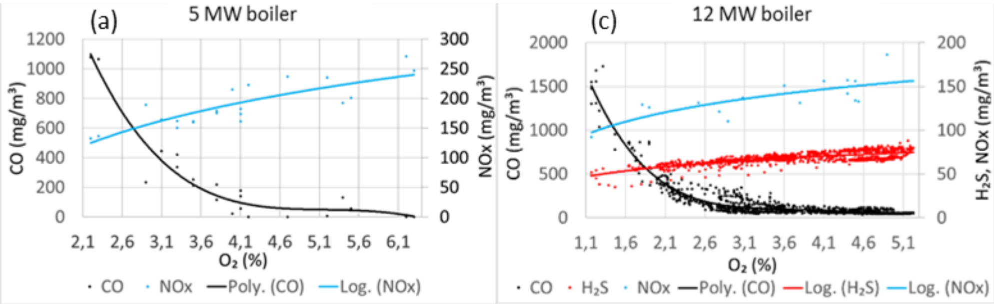

Fig. 1.9. The dependence of flue gas emissions of 5 MW (a) and 12 MW (b) industrial boilers on O_2 concentration in flue gas during the combustion of wood chips

The measurements of CO, NOx and H_2S emissions in the industrial boiler show the same trends compared to experimental stand. At the same 5% O_2 concentration, the NOx concentration in the 5 MW boiler (Fig. 1.9 a) was 210 mg/m^3 and in the 12 MW (Fig. 1.9 b) it was 155 mg/m^3. This difference in NOx emissions occur due to different fuel quality and combustion conditions.

In the experimental stand, research was performed by combining means of reducing excess air and selective reagent supply by burning sunflower hull pellets. By setting baseline emission values, excess air was gradually reduced by generating CO concentrations of 100–500 mg/m^3 and 1000–2000 mg/m^3. After exposure to CO, the studies were repeated with an additional supply of 32.5% urea solution. The amount of urea solution (0.65% by weight of fuel) was selected on the basis of previous tests when the NH_3 concentrations were minimal. The results are shown in Figure 1.10.

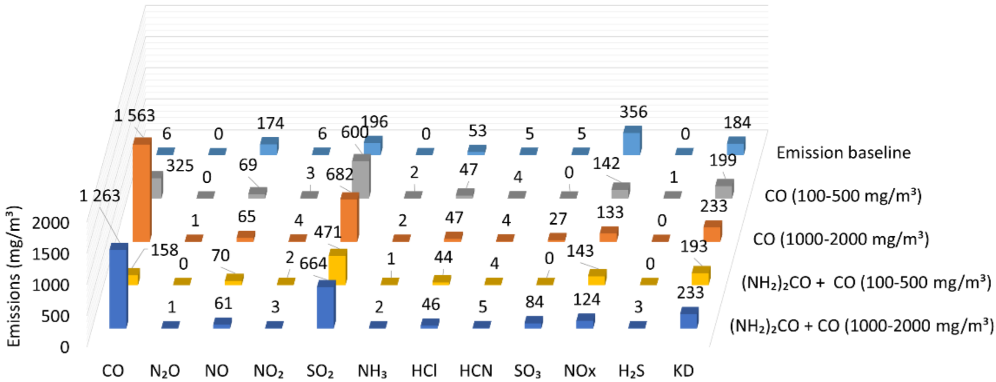

Fig. 1.10. The dependence of Enerstena's experimental stand flue gas emissions on the combination of reduction measures during the combustion of sunflower hull pellets

Baseline NOx values (without any measures) were 356 mg/m^3. By maintaining CO concentrations between 1000 mg/m^3 and 2000 mg/m^3, NOx and NO concentrations decreased to 133 mg/m^3 and 65 mg/m^3, respectively. The concentrations of NO_2, NH_3, HCN, and H_2S did not exceed 5 mg/m^3. Baseline SO_2 concentrations were 196 mg/m^3. At CO levels of 1000–2000 mg/m^3, SO_2 emissions increased to 682 mg/m^3. SO_3 was unstable and ranged from 5 mg/m^3 to 27 mg/m^3. The combination of urea and excess air measures resulted in more pronounced differences in results. With the supply of $(NH_2)_2CO$ and maintaining the same level of CO, the NOx values were 124 mg/m^3. The concentrations of NO decreased to 61 mg/m^3 compared to baseline emissions. NO_2, N_2O, NH_3, HCN, and H_2S increased slightly but did not exceed 7 mg/m^3. At the same time, SO_2 concentrations increased to 664 mg/m^3 and SO_3 concentrations increased to 84 mg/m^3. Particulate matter (PM) measurements show that concentrations are independent of urea supply. PM concentrations increased from 184 mg/m^3 to 233 mg/m^3 both with excess air reduction and in combination with urea supply.

The significant increase in SO_2 concentrations can be explained by the influence of CO. During combustion, the Ca and S elements in the fuel react with each other to form calcium sulfate, which settles on the surfaces of the furnace, boiler, and subsequent flue gas tract installations. Lupiáñez et al. [40] performed experiments investigating SO_2 emissions under fluidized bed combustion conditions and found that at temperatures above 850°C, carbon monoxide can induce the release of SO_2 from $CaSO_4$. CO reacts with $CaSO_4$-containing fly ash and furnace and boiler deposits to release CaO, CO and SO_2.

Combined influence of flue gas recirculation and CO

Typically, flue gas recirculation in boilers is used to reduce the temperature in the furnace, thus avoiding the formation of "thermal NOx". The combustion of relatively high humidity and low calorific biofuels does not produce "thermal NOx", so all NOx emissions are "fuel NO". The formation of NOx in the fuel has little effect on temperature, but the concentrations of NOx have been observed to decrease with the supply of recirculated flue gas with primary air. More detailed studies of the influence of combined primary measures – flue gas recirculation and excess air on nitrogen and sulfur gaseous compounds have been carried out by the author of the dissertation in an international peer-reviewed journal [89].

During the research, temperature and emissions measurement were investigated. It was determined that the flame temperature above the grate can be reduced from 890°C to 750°C by applying 50% flue gas recirculation. In the secondary combustion zone, the temperature remains practically constant at 980°C. Emissions were determined by creating different flue gas recirculation ratio and combustion quality. The flue gas recirculation was gradually increased and the excess air was reduced, thus creating different CO concentration levels: up to 200 mg/m^3 (Fig. 1.11 a); from 300 mg/m^3 to 500 mg/m^3 (Fig. 1.11 b); from 1000 to 1500 mg/m^3 (Fig. 1.11 c); from 2000 to 2500 mg/m^3 (Fig. 1.11 a).

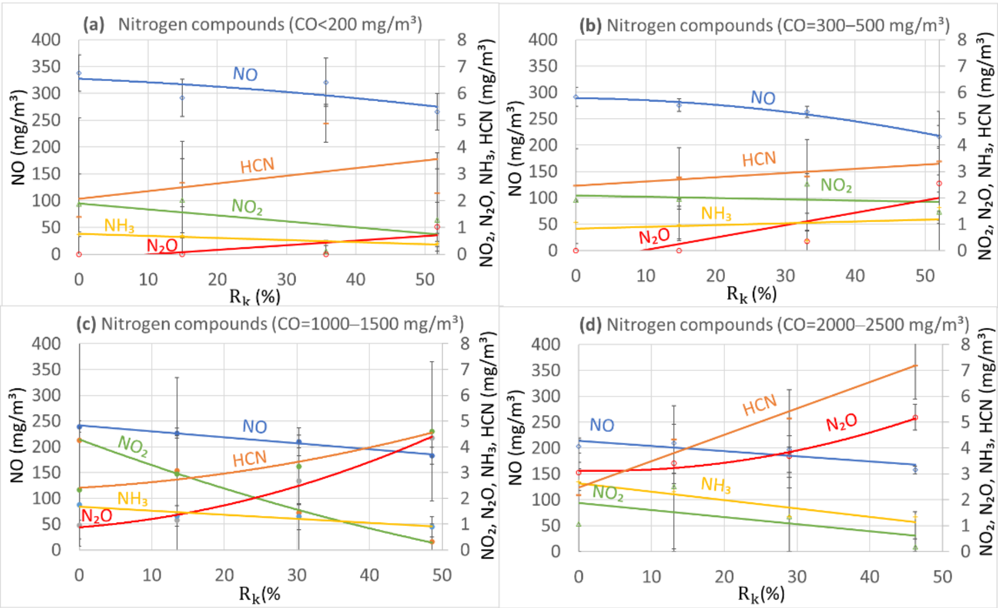

Fig. 1.11. The dependence of the Kaunas University of Technology experimental stand flue gas nitrogen compounds emissions on the combination of flue gas recirculation with primary air and carbon monoxide during combustion of sunflower hull pellets

Maximum NO concentrations, i.e., 340 mg/m^3 measured at maximum excess air with CO < 200 mg/m^3 with flue gas recirculation switched off. By reducing excess air, NO concentrations decreased to 250 mg/m^3, and by increasing flue gas recirculation, NO concentrations decreased by 50–80 mg/m^3. NO_2 and NH_3 showed similar trends but their concentrations did not exceed 4 mg/m^3. The concentrations of

HCN showed opposite trends. Their lowest concentrations did not depend on excess air and in all cases ranged from 100 mg/m^3 to 120 mg/m^3, but the highest concentrations depended on both CO and flue gas recirculation and amounted to 350 mg/m^3.

The influence on sulfur gas was also investigated (Fig. 1.12 a, b, c, d). The measurements of SO_2 emissions have shown that concentrations increase from both flue gas recirculation and CO levels. The lowest SO_2 concentration was measured at the lowest CO concentration and the flue gas recirculation switched off and was 60 mg/m^3. These trends are reversed compared to NOx. Increasing CO concentrations to 1000–2000 mg/m^3 increased SO_2 emissions to 150 mg/m^3. Flue gas recirculation increases SO_2 emissions by 60–120 mg/m^3. SO_3 and H_2S emissions showed opposite trends. SO_3 concentrations were practically stable at 10 mg/m^3, only in the case of partial combustion did the additional supply of flue gas recirculation reduce the concentrations by 5 mg/m^3. The concentrations of H_2S gradually decreased with increasing CO emissions and increasing flue gas recirculation. Particularly high instability of H_2S values is observed in the absence of air, when CO was between 2000 mg/m^3 and 2500 mg/m^3.

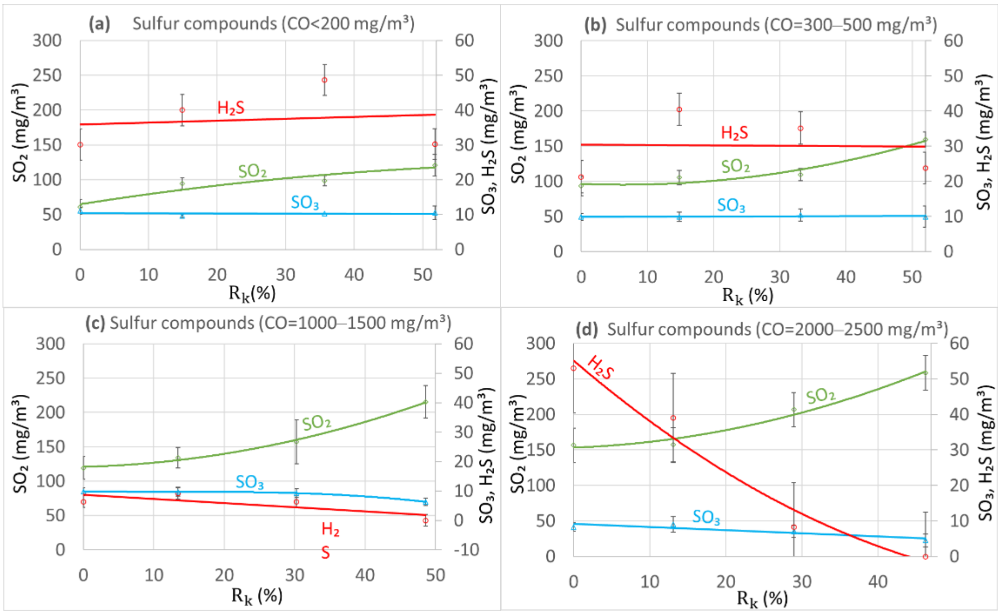

Fig. 1.12. The dependence of the Kaunas University of Technology experimental stand flue gas sulfur compounds emissions on the combination of flue gas recirculation with primary air and carbon monoxide during combustion of sunflower hull pellets

Based on the sulfur content of the sunflower hull pellets (Table 1.1), the theoretical maximum SO_2 concentration could have reached approximately 270 mg/m^3 at full S conversion to SO_2, but measurements show that much lower SO_2 concentrations are formed under real combustion conditions. Flame spectrum measurements on the experimental stand and an 8 MW industrial boiler were characterized by clear spectral peaks at 589 nm and 769 nm, which correspond to the wavelengths of Na and K ions. This indicates that salt formation occurs in the flame above the fuel layer. The supply of flue gas recirculation reduces the activity of Na and K as the flame temperature decreases, which reduces the formation of K_2SO_4 and Na_2SO_4 salts. The analysis of the elemental composition of the ash from the furnace, the furnace walls, the boiler surfaces, and the ash of the cyclones confirms this – a part of the sulfur is present in the particulate matter. For this reason, flue gas recirculation affects the SO_2 concentrations.

The reduction in NOx concentrations through flue gas recirculation can be explained by several mechanisms. Liu et al. [93] summarized three NOx reduction mechanisms: 1) flue gas recirculation has a positive effect on reducing NOx concentrations by lowering the combustion temperature by diluting the flue gas with inert gas, but this measure is more suitable for reducing thermal NOx; 2) flue gas recirculation reduces the partial pressure of oxygen and the rate of reactions during combustion due to lower temperature and reduced concentration of reactive components; 3) flue gas recirculation causes combustion instabilities, which reduces fast NOx concentrations. Yin et al. [41] also found a positive effect of flue gas recirculation on reducing NOx concentrations. Internal flue gas recirculation forms vortex zones. Due to the increased path and residence time of combustion products, the oxidation conditions of CO and volatile substances improve. Intensive NOx and CO conversion takes place in these vortex zones. At the same time, flue gas recirculation reduces the temperature of combustion products and the likelihood of thermal NOx formation.

Combined influence of CO, flue gas recirculation and solid reagents on flue gas composition

Calcium compounds are most commonly used for flue gas desulfurization in industrial boilers. They are usually injected into a low-temperature (below 200°C) flue gas stream, but the influence of these calcium reagents on other compounds, e.g., nitrogen for gaseous compounds has not been sufficiently studied and is not clear. Reagents of CaO, CaOH, $CaCO_3$, $NaHCO_3$, and kaolin ($H_2Al_2O_8Si_2.H_2O$) were tested during the experiments. The effect on SO_2 was shown only by calcium compounds, of which CaO had the best effect. Therefore, in the experimental stand, studies were performed to determine the total effect of calcium oxide on the emissions of sulfur and nitrogen compounds. When burning sunflower hull pellets, CaO was injected into separate furnace locations: above the fuel layer and into the final combustion zone. The optimal CaO content, i.e., 5.4% by mass of fuel selected on the basis of the results of the original tests. The supply of CaO above the fuel bed and to the final combustion zone had virtually the same effect on NOx and NO concentrations, reducing NOx from 194 mg/m^3 to an average of 141 mg/m^3 and NO from 95 mg/m^3 to 69 mg/m^3. The NOx reduction effect may have been due to the increase in CO emissions caused by the cooling of the furnace due to the pneumatic injection of CaO. Irrespective of the CaO injection site, a slight reduction in NH_3, HCN, and SO_3 and an increase in NO_2 emissions were measured, although in all cases the concentrations did not exceed 10 mg/m^3.

Studies have been carried out in an experimental stand to determine whether the CaO content in the fuel itself affects the flue gas composition. Studies were performed with sunflower hull pellets: without the addition of CaO, with the addition of 0.5% CaO, and with the addition of 1.0% CaO. The emission results are shown in Figure 1.13. It is observed that SO_2 concentrations are related to CO emissions, therefore a more detailed analysis was performed to determine the impact of combined excess air and flue gas recirculation measures on NOx and SO_2 emissions when burning sunflower hull pellets with 0%, 0.5% and 1.0% CaO. Excess air was adjusted to maintain different CO concentrations: up to 100 mg/m^3; between 100 mg/m^3 and 200 mg/m^3; above 200 mg/m^3.

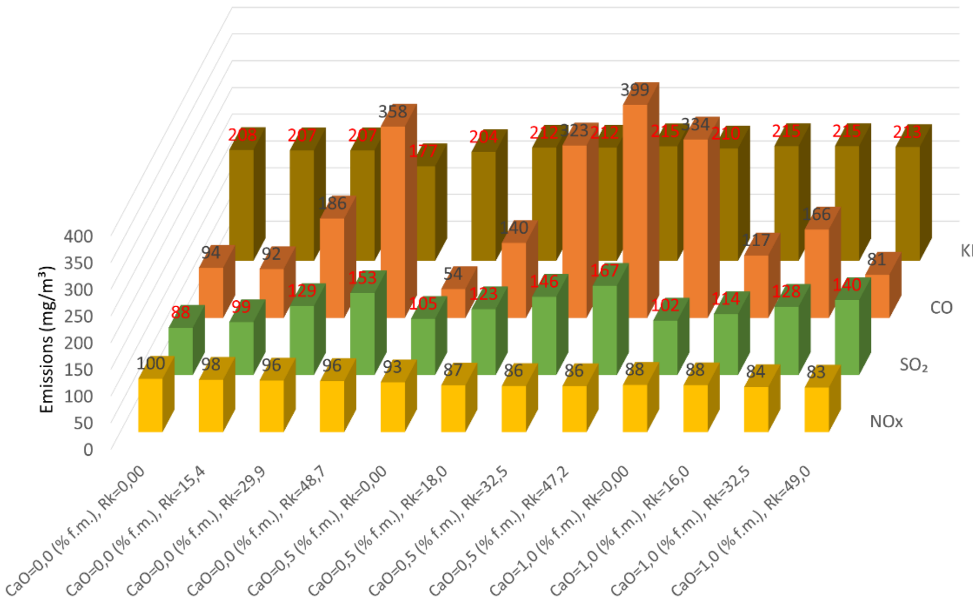

Fig. 1.13. The dependence of Enerstena's experimental stand flue gas emissions on the combination of flue gas recirculation with primary air, carbon monoxide concentrations, and CaO quantity during the combustion of sunflower hull pellets

When burning sunflower hull pellets without flue gas recirculation and CaO additive, the measured maximum NOx emission concentration was 100 mg/m^3. The lowest NOx concentrations were achieved with flue gas recirculation of Rk – 49% and CaO content of 1% in the fuel. The insignificant decrease in mean NOx concentrations may have been due to the inhibitory effect of CaO on combustion and the decrease in flame temperature. It is determined that SO_2 concentrations are unrelated to the amount of CaO in the fuel. SO_2 increased from 38 mg/m^3 to 65 mg/m^3 depending only on the flue gas recirculation. In most cases, CO emissions also increased as a result of flue gas recirculation, but at a CaO content of 1% in the fuel, this dependence is not clearly expressed. Particulate matter (PM) concentrations remained stable in almost all cases and were independent of CaO content in the fuel or flue gas recirculation. Measurements of PM and SO_2 concentrations show that sulfur conversion takes place only in the gas phase. i.e., above the fuel layer. PM measurements showed that the lime remained in the fuel layer and therefore could not react with the sulfur.

When burning fuel without flue gas recirculation, the difference in NOx, depending on CO levels, is up to 5 mg/m^3. Increasing the amount of flue gas recirculation increases the NOx difference to 10 mg/m^3. The difference in NOx concentrations at different CO levels is not as pronounced only when burning fuel with 1% CaO added in the fuel.

Calculation methodologies to assess the effectiveness of NOx and SO_2 reduction measures

Based on the performed experimental studies, calculation methodologies were developed to estimate the effect of the studied emission reduction measures on the concentration of NOx and SO_2 in the boiler flue gas. Measures on emissions cannot be arithmetically summarized, thus the presented methodology allows to calculate emissions according to NOx and SO_2 reduction methods separately. These methods can be applied to reciprocating grate fires using solid biomass fuels with a nitrogen content of up to 0.51% and a sulfur content of up to 0.08%.

The most typical graphs of emission reduction measures were used to develop the calculation methodology. Data of which were processed to determine the dependence of the emissions on the scope of the measure applied.

NOx calculation method

The calculation of NOx emissions by estimating the effect of partial combustion products (CO concentration):

$$NOx_{(CO)} = NOx_{p.r.}(1.80 - 0.15 \ln CO) \quad (1.1)$$

here:

$NOx_{(CO)}$ – the concentration of the pollutant under the influence of partial combustion (CO) products (mg/m^3);

$NOx_{(p.r.)}$ – NOx concentrations without reduction measures (mg/m^3);

CO_k – carbon monoxide concentration in flue gas (mg/m^3).

Calculation of $NOx_{(p.r.)}$:

$$NOx_{(p.r.)} = K_{NOx} NOx_{(teor.)} \quad (1.2)$$

here:

K_{NOx} – a factor estimating which part of the nitrogen in the fuel is converted to NOx. According Pleckaitiene et al. [15]: 0.07–1.0;

$NOx_{(teor.)}$ – theoretical NOx values under complete nitrogen oxidation.

The calculation of NOx emissions by estimating the effect of flue gas recirculation:

$$NOx_{(d.rec.)} = NOx_{(p.r.)}(1 - 0.00424R_k) \quad (1.3)$$

here:

$NOx_{(d.rec.)}$ – the concentration of the pollutant under the influence of flue gas recirculation (mg/m^3);

R_k – flue gas recirculation ratio (%).

The calculation of NOx emissions by estimating the effect of $(NH_2)_2CO$ in an experimental stand:

$$NOx_{((NH2)2CO)} = \frac{NOx_{(p.r.)}}{283} \cdot e^{-0.191u} \quad (1.4)$$

here:

$NOx_{((NH2)2CO)}$ – the concentration of the pollutant under the influence of $(NH_2)_2CO$ in an experimental stand (mg/m^3);

u – the quantity of $(NH_2)_2CO$ (kg/MW).

The calculation of NOx emissions by estimating the effect of $(NH_2)_2CO$ in an industrial boiler:

$$NOx'_{((NH2)2CO)} = NOx_{(p.r.)}(1 - 1.44u + u^2 - 0.22u^3) \quad (1.5)$$

here:

$NOx'_{((NH2)2CO)}$ – the concentration of the pollutant under the influence of $(NH_2)_2CO$ in an industrial boiler (mg/m^3).

SO_2 calculation method

The calculation of SO_2 emissions by estimating the effect of partial combustion (CO concentration):

$$SO_{2(CO)} = SO_{2(p.r.)}(0.6 \ln CO) - 2 \quad (1.6)$$

here:

$SO_{2(CO)}$ – the concentration of the pollutant under the influence of partial combustion (CO) products (mg/m^3);

$SO_{2\,(p.r.)}$ – SO_2 concentrations without reduction measures (mg/m^3);

CO – carbon monoxide concentration in flue gas (mg/m^3).

The calculation of $NOx_{(p.r.)}$:

$$SO_{2_{(p.r.)}} = K_{SO_2} SO_{2(teor.)} \tag{1.7}$$

K_{SO_2} – a factor estimating which part of the nitrogen in the fuel is converted to SO_2. According to Roy et al. [25]: 0.57–0.65.

$SO_{2(teor.)}$ – theoretical SO_2 values under complete nitrogen oxidation.

The calculation of SO_2 emissions by estimating the effect of flue gas recirculation:

$$SO_{2_{(d.rec.)}} = SO_{2_{(p.r.)}}(0.0154 R_k) \tag{1.8}$$

here:

$SO_{2(d.rec.)}$ – the concentration of the pollutant under the influence of flue gas recirculation (mg/m^3);

R_k – flue gas recirculation ratio (%).

The calculation of SO_2 emissions by estimating the effect of $(NH_2)_2CO$ in an experimental stand:

$$SO_{2_{((NH2)2CO)}} = \frac{SO_{2_{(p.r.)}}}{30} \cdot e^{-0.051u} \tag{1.9}$$

here:

$SO_{2\,((NH2)2CO)}$ – the concentration of the pollutant under the influence of $(NH_2)_2CO$ in an experimental stand (mg/m^3).

The calculation of SO_2 emissions to evaluate the effect of CaO above the fuel layer in an experimental stand:

$$SO_{2_{(CaO)}} = SO_{2_{(p.r.)}}(1 - 0.0062w) \tag{1.10}$$

$SO_{2(CaO)}$ – the concentration of the pollutant under the influence of CaO above the fuel layer (mg/m^3);

w – CaO quantity (kg/MW).

The calculation of SO_2 emissions to evaluate the effect of CaO at the final combustion zone:

$$SO_2{}'_{(CaO)} = SO_{2(p.r.)}(1 - 0.01w) \tag{1.11}$$

$SO_2{}'_{(CaO)}$ – the concentration of the pollutant under the influence of CaO at the final combustion zone (mg/m^3).

CONCLUSIONS

1. The cause of periodic fluctuations in the composition of combustion products is the reversal of the fuel layer and the opening of grate air slots in the main combustion zone, which is caused by the movement of grate in the biofuel furnaces. This changes the combustion regime of gaseous pyrolysis products. Fluctuations in the concentrations of nitrogen and sulfur compounds are influenced by the level of their concentrations, which depends on the nitrogen and sulfur content of the fuel;

2. The injection of urea into biofuel combustion products at 950–1050°C reduces the concentrations of NO, NO_2, SO_2, and H_2S. When 1% of urea from fuel mass is supplied, the reduction of concentrations differs for different compounds: NO – 57%, NO_2 – 100%, SO_2 – 19%, H_2S – 90%. In industrial boilers, the NOx reduction is up to 67%. When combustion takes place with CO generation and low NOx concentrations are reached, the additional effects of urea supply have little effect. The urea supply also reduces the concentrations of SO_2, therefore the combination of these measures makes it possible to reduce both emissions;

3. Recirculation of combustion products together with primary air reduces the concentrations of NO, NO_2, NH_3, SO_3 and H_2S, but increases the concentrations of SO_2, HCN and N_2O. The intensity of these changes depends on the completeness of fuel combustion, i.e., on the concentration of CO in the combustion products. During the combustion of biofuels, when the flue gas recirculation ratio is 50% and CO = 2000–2500 mg/m^3, NOx concentrations can be reduced by 50%, but SO_2 concentrations quadruple and approach the maximum theoretical values. Flue gas recirculation and partial combustion mode cause an increase in SO_2 concentration, so these methods must be combined with flue gas desulfurization measures;

4. Experiments on moving grate stands, domestic and industrial boilers have shown that the dependence of emissions on the concentration of oxygen in the flue gas is similar and does not depend on the combustion plant or type of fuel. The nature of the change in nitrogen and sulfur concentrations indicates a greater dependence on CO than on O_2 concentrations in flue gas;

5. Mixing CaO with fuel does not affect the concentrations of SO_2 and H_2S. The supply of CaO into the final combustion zone is 10% more effective in reducing SO_2 concentrations compared to the supply above the fuel bed. This indicates that the formation of SO_2, SO_3, and H_2S takes place mainly in the combustion zone of gaseous products of biofuel pyrolysis. For these reasons, CaO must be supplied to this zone.

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CURRICULUM VITAE

Adolfas Jančauskas 2010 metais įgijo vidurinį išsilavinimą Kauno „Aušros“ gimnazijoje. 2014 m. baigė Aleksandro Stulginskio universiteto studijas ir įgijo energijos inžinieriaus bakalauro laipsnį. 2016 m. įgijo energijos inžinieriaus magistro kvalifikacinį laipsnį Kauno Technologijos universitete. 2017 m. įstojo į KTU doktorantūros studijas termoinžinerijos srityje.

Studijų metu disertantas aktyviai dalyvavo moksliniuose projektuose. Nuo 2017 metų dalyvavo kuriant inovatyvius produktus skirtus pramoninių biokuro katilų taršos mažinimui „Intelektas“ projekte “Biokuro panaudojimo veiksmingumo didinimo bei taršos mažinimo technologijų tyrimas ir kūrimas”, Nr. J05-LVPA-K-01-0161 (jungtinis verslo ir mokslo projektas tarp UAB “Enerstena”, KTU, LEI). Nuo 2018 dalyvavo KTU projekte “BioFlame: Biokuro degimo automatinis valdymas pagal biokuro liepsnos emisines charakteristikas” (Nr. PP32/1811). 2020 metų įtrauktas į „Eksperimentas“ projektą „Daugiafunkcinės Biomasės Energetikos Technologijos MultiBET“ Nr. 01.2.1-LVPA-K-856-01.

Adolfas Jančauskas organizuoja užsiėmimus Kauno miesto moksleiviams. Yra apdovanotas švietimo ministro padėka už mokinių techninės kūrybos gebėjimų ugdymą ir yra oficialus Lietuvos rekordininkas.

MOKSLINIŲ STRAIPSNIŲ IR MOKSLINIŲ KONFERENCIJŲ SĄRAŠAS

STRAIPSNIAI RECENZUOJAMUOSE MOKSLO LEIDINIUOSE

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MOKSLINIŲ KONFERENCIJŲ SĄRAŠAS
Autoriaus pranešimai konferencijose disertacijos tema

1. 2018 m. „Šilumos energetika ir technologijos 2018“ konferencijoje skaitytas pranešimas „Selektyvinės nekatalitinės NOx šalinimo sistemos efektyvumo tyrimai“;
2. 2019 m. „Šilumos energetika ir technologijos 2019“ konferencijoje skaitytas pranešimas „NOx emisijų mažinimo sistemos bandymai pramoniniame biokuro katile“;
3. 2019 m. tarptautinėje konferencijoje „ISES ISIAQ 2019 Joint Annual Meeting“ atliktas pranešimas „Engineered wood residues as a boiler fuel: potential impacts on air quality“;
4. 2020 m. tarptautinėje konferencijoje „Проблемы экологии и эксплуатации объектов энергетики“ („Ekologijos ir energetikos objektų eksploatavimo problemos“) atliktas pranešimas „Селективное некаталитическое снижение NOx в котлах, сжигающих биомассу“ („Biomasės katilų selektyvusis nekatalitinis NOx redukavimas“);
5. 2021 m. tarptautinėje konferencijoje „INDUSTRIAL ENGINEERING 2021“ atliktas pranešimas „Investigations of NOx and SO2 Emmisions reduction Measures in Biofuel Boilers“;
6. 2021 m. tarptautinėje konferencijoje „Проблемы экологии и эксплуатации объектов энергетики“ („Ekologijos ir energetikos objektų eksploatavimo problemos“) atliktas pranešimas „ВЫБРОСЫ NOX и SO2 ПРИ СЖИГАНИИ ОТХОДОВ ПИЩЕВОЙ И МЕБЕЛЬНОЙ ПРОМЫШЛЕННОСТИ“ („NOx ir SO2 emisijų susidarymas deginant maisto ir baldų pramonės atliekas“).

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