Methods of Nitrogen Oxide Reduction in Pellet Boilers

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Abstract - **The main goal of this research was to create and test technical solutions that reduce nitrogen oxide emissions in low-capacity pellet boiler. During the research, wood pellets were incinerated in a pellet boiler produced in Latvia with a rated capacity of 15 kW. During the research two NO_x emission reduction methods were tested: secondary air supply in the chamber and recirculation of flue gases. Results indicated a drop of NOx concentration only for flue gas recirculation methods. Maximum reduction of 21% was achieved.**

Keywords - NO_x emissions, pellet boiler, NO_x emission reduction.

I. Primary Nitrogen Oxide Reduction During a Process of Biomass Combustion

There are three types of nitrogen oxides NO_x known depending on the mechanisms of their origin:
- Thermal – Zeldovich mechanism;
- Prompt – Fenimore mechanism;
- Fuel.

Among many factors impacting a formation of nitrogen oxides in furnaces, the followings can be distinguished [1]:
- Concentration of components in the thermo-chemical reactions taking place in a combustion zone;
- Retention time of components and combustion products in a reaction zone;
- Temperature level in a reaction zone.

Thermal oxides are formed by the oxidation of nitrogen in air impacted by high temperatures. Essential concentrations of oxides can be observed if the temperature in the combustion zone is > 1300°C [2,3,4].

In the formation of prompt nitrogen oxides molecular nitrogen in air is involved by reacting with intermediate product of hydrocarbons [3].

The formation of fuel oxides is generally determined by the nitrogen content in the fuel but this is not the only determing factor. In practice, it can be observed that when the effective combustion rules overviewed above (air consumption is higher than stehiometric, high temperature, longer retention time) are reached, the level of fuel oxides is higher [5].

Experimental researches on biomass combustion show that only fuel nitrogen oxides are important [5]. The relative importance of thermal, prompt and fuel nitrogen oxides for biofuels of different types depending on temperature are shown in Figure 1.

During the experiments [5] wood pellets, herbaceous biomass and used wood chip boards and wood were used. Fuels vary with nitrogen content part of mass of which changes from 0,15% in the case of wood chips up to 2% for used wood or wood chip boards.
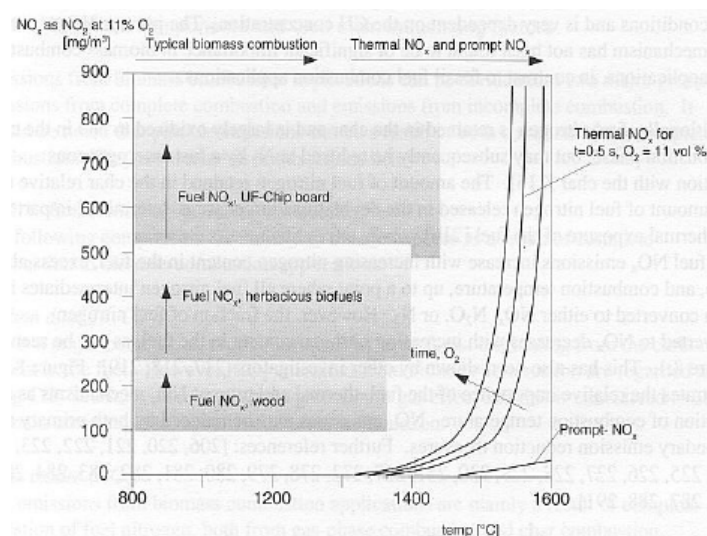

Fig. 1. NO_x emission levels for different types of biofuel depending on temperature [5].

As the temperature in furnaces of biomass combustion equipment is within 800 – 1200°C it can be observed that thermal as well as prompt nitrogen oxides are insignificant. It has to be noted that oxygen content and retention time in the combustion zone are important for every forming mechanism of nitrogen oxides. When these parameters increase, an amount of nitrogen oxides increases. An arrow in the right lower corner of Fig. 1 shows this correlation.

The results of experimental researches [6] on changes of nitrogen oxides formation depending on the nitrogen content of the fuel are shown in Figure 2.

Research indicates that an increase of fuel nitrogen content creates an increase in the nitrogen oxides level which is stated as mg/nm^3 (oxygen content of flue gas 10%) in one research [6] and mg/MJ (fuel) in another research [8]. But as can be seen in Figure 2, by increasing the nitrogen amount in fuel, the part of nitrogen which is transformed into oxides decreases.

The end result of fuel nitrogen transformation in the process of combustion can be nitrogen oxides, atomic nitrogen or nitrogen discharged with ashes. Overall it can be asserted that an

amount of discharged nitrogen oxides are equal with the produced amount of oxides, except the amount of oxides degraded during the reactions of reduction [9]. The possible reactions of fuel nitrogen during the process of combustion are illustrated in Figure 3.
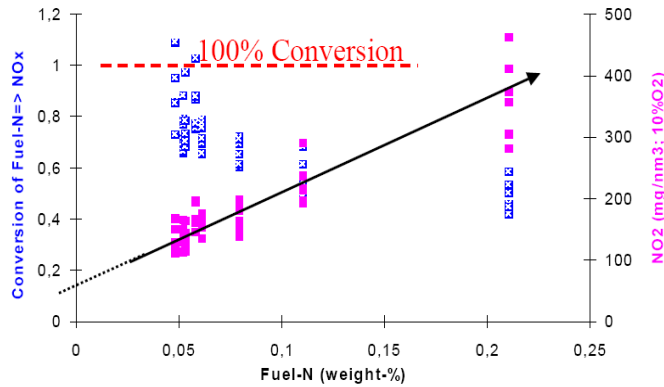

Fig. 2. Formation of NO_x emissions in boilers combusting pellets with different nitrogen content [6,7].
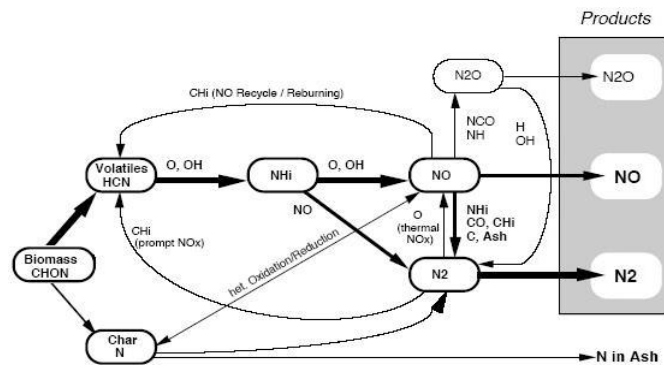

Fig. 3. Formation of NO_x emissions in the boilers combusting pellets with different content of nitrogen [6].

In the diagram, the reactions of fuel nitrogen which take place both in the gaseous (combustion of volatile substance) and solid (combustion of coke) state can be tracked. It can be observed that the end products of fuel nitrogen conversion are nitrogen oxides, molecular oxides and nitrogen presented in the content of biomass ashes.

II. PRIMARY NITROGEN OXIDES REDUCTION WITHIN THE PROCESS OF BIOMASS COMBUSTION

Technologies applying separated air and fuel injection as an effective method for primary NO_x reduction are rapidly developing within the last 10 years. The base of processes of primary NO_x reduction is previously observed conception. As it was mentioned before, separated air injection ensures both effective fuel combustion and a reduction of nitrogen oxides. To make the reduction of nitrogen oxides possible, the phase of the formation and combustion of volatile substances has to be separated from the total combustion of gaseous products, creating a reduction zone. The reduction zone has to be large enough to ensure the required retention time in the reduction zone for reaction components necessary for reduction reac-

tions. In the reduction zone, combustion of a rich mixture is taking place in conditions with an air deficit. The total combustion of fuel is achieved by the injection of secondary air after the reduction zone. The principles of separated air and fuel injection are schematically shown in Figure 4.
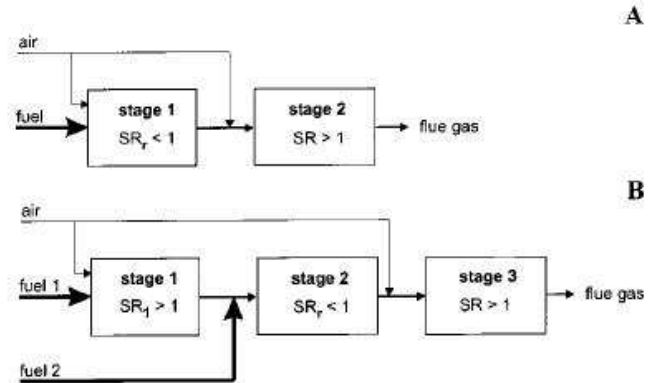

Fig. 4. A principle of separated air (A) and fuel (B) supply.

As it can be observed in the case (A) of Figure 4, combustion in the first stage takes place in conditions when the air consumption coefficient < 1. This means that molecular nitrogen forms during the fuel nitrogen reactions. Ensuring a good mix of first level combustion products with secondary air, the total fuel combustion and small total air consumption can be achieved.

A principle of separated fuel combustion is shown in case (B) of Figure 4. Applying this principle of fuel combustion in the first stage, fuel combustion takes place in conditions where air consumption is a little higher than stechiometrically necessary. This is a reason why the formation of nitrogen oxides can be observed. Then an additional fuel is added which getting mixed with the combustion products of the previous stage creates conditions for rich fuel mixture combustion with an air consumption coefficient < 1. Under the conditions of air insufficiency previously created, the nitrogen oxides, reacting with NH_3 and HCN in reduction zone are reduced, thus creating molecular nitrogen. This process is similar to the one which occurs in case of separated air injection. If, in the case of separated air injection, a zone where combustion takes place under the conditions of an air deficit is called the reduction zone, then, in the case of separated fuel injection – reburning zone.

In the end of the combustion process, an amount of air necessary to complete combustion is injected. At this stage, the air consumption coefficient is >1. In this way, the complete combustion of fuel is achieved with a minimal level of nitrogen oxides emissions. The total air consumption coefficient of fuel combustion is λ > 1. It must be noted that, in the case of separated fuel supply, the temperature in the reduction zone is lower (approximately 800°C) compared with 1100-1200°C, which is the case when applying the principle of separated air injection. This can be very crucial in the case when the fuel has a low ash melting temperature. Ordinarily, the melting temperature of wood ash is approximately 1300°C. It is significantly lower (from 800-900°C) in the case of herbaceous biomass and recycled wood which is associated with the larger

content of inorganic substances which can create compounds with low melting temperatures.
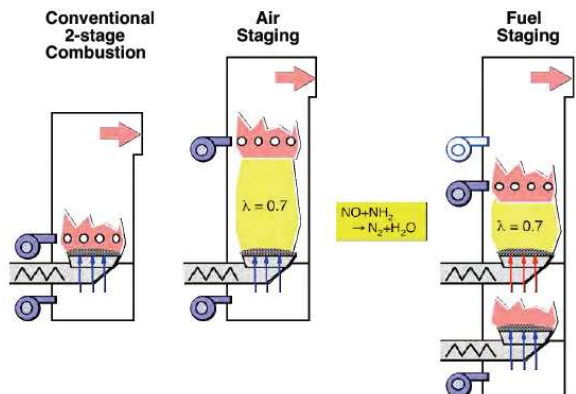

Fig. 5. Three principles of complete fuel combustion [10, 11].

The methods of fuel combustion shown in Figure 5 have several common features. In all cases fuel is combusted completely and effectively and it is done using separated air injection. In the "Conventional 2-stage Combustion", the primary air is injected under the grates in the fuel layer with $\lambda < 1$. Complete combustion is achieved with the help of secondary air, which is injected into the volatile substance in the combustion zone above the grate with $\lambda < 1$. Both zones are located in the same area. This is the way combustion takes place in modern energy efficient biomass boilers.

The scheme in the middle differs from the previous one in that the primary and secondary place for air injection are located in separated areas, which creates a reduction zone. It is done in the case if a primary NO_x reduction in boilers is provided. By constructing a reduction zone, the dimensions of a boiler increase and the boiler becomes more constructively complicated. The coefficient of air consumption and the reduction reaction occurring is shown in Figure 5. Separated air and fuel inflow are shown in the "Fuel staging". Here the reduction zone develops between the secondary fuel and air injection.

III. DESCRIPTION OF EXPERIMENTAL BOILER

Within this research some constructive solutions for nitrogen oxide reduction are applied and verified under real conditions. For the experiment a pellet boiler with a nominal capacity of 15 kW produced in Latvia was chosen.

A principal scheme of the furnace of the pellet boiler is shown in Figure 6. A pellet supply screw is inserted into an air injection channel but it is separated from the air injection system. Pellets are supplied through the bottom of the burner. The boiler has a compulsory air injection system fitted with a centrifugal ventilator. For the combustion process, air is injected in the burner in two levels.

A portion of air is injected into the pellet layer through the small clefts in the bottom of the burner but the other portion of air is injected through clefts in the top of the burner under a cone.
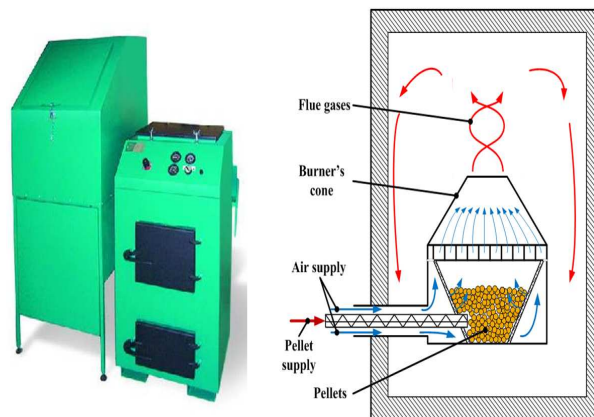

Fig. 6. Pellet boiler Grandeg GD-WB 15 and a sketch of the boiler's furnace.

The air injection clefts are placed along the overall perimeter of the burner and air is injected in spiral way. Due to this solution, the flame is turned and creates a swirl. The flue gases developed in the process of combustion is returned to the bottom of the furnace where they are drained to the heat exchange pipe system.

IV. DESCRIPTION OF THE EXPERIMENTAL STAND

In order to conduct the experiments, a boiler testing stand was used. It is placed in the Laboratory of Environmental Monitoring of the Riga Technical University. The developed stand makes it possible to test small capacity boilers according to the methodology of standard LVS EN 303-5 [12]. A principal scheme of the stand is showed in Figure 7.

A heat load in the stand is developed using a compulsory air convection cooler. If the cooling capacity is not enough, a water accumulation tank is used as an additional cooler.

In order to determine the energy efficiency of the boiler, a direct method is used and it is based on the ratio between effectively produced heat energy and the consumed fuel chemical energy.

During the boiler testing, a monitoring of flue gas temperature, chemical content and measurements of solid particles are performed. Additionally, rarefactions in the funnel are determined and controlled. The flue gas temperature is determined in five different places in the funnel using K-type thermocouples. A concentration of solid particles is measured using an isokinetic flue gas sampler. The operational principles of the equipment are based on isokinetic gas sampling and gravimetric method of solid particle determination.

Oxygen content in the flue gases is determined using a magneto-mechanical stationary analyzer. Carbon dioxide, carbon monoxide and nitrogen monoxide content in the flue gas is determined using an infrared absorption analyzer. Nitrogen dioxide concentration is determined with an electrochemical analyzer.

Boiler testing is done under nominal boiler operational conditions i.e. water flow – 0,6 m³/h, water return temperature 50°C and rarefaction in funnel - ≤ -20 Pa. The minimal time of one complete test is six hours. Testing is initiated after achieving stable boiler performance parameters.
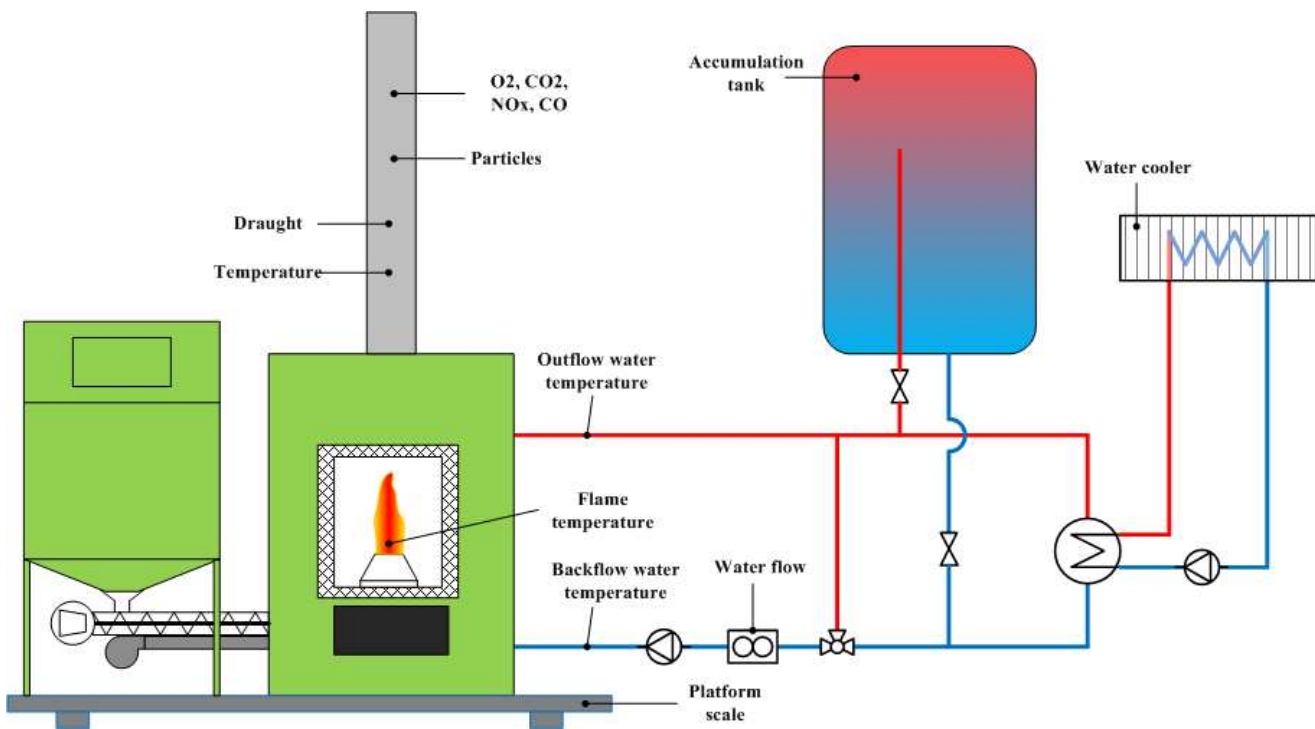
Fig. 7. Principal scheme of boiler testing stand.

The results of the measurements were recorded during the testing. Measurements of the solid particle concentration were done four times during each test. The duration of one measurement is 30 minutes.

For realization of the experiment, the pellets produced of sawdust of deciduous trees in Latvia were used. During the process of the production of pellets used in the experiment, no chemical cohesive substances were used. The average diameter of pellets is 6.25 millimeters and the characteristic length – 16.2 mm. For the quantitative evaluation of the pellet quality in the Laboratory of Environmental Monitoring of the Riga Technical University, characteristic parameters were determined: ash content, moisture, net and gross calorific value, volume density, amount of cutting and mechanical durability. The determination of parameters was done according to solid biofuel standards CEN/TS released by European Committee for Standardization CEN (TC335). The values of parameters characterizing pellet quality are shown in Table 1.

To keep the representation of pellets used in experiment for the duration of the experiment at one level, they were kept in hermetically-sealed packages.

V. METHODS USED FOR REDUCTION OF NO_x EMISSIONS

During the research two mechanisms for NO_x emissions reduction were examined. One of the mechanisms is the injection of additional air into the furnace; the other is flue gas recirculation and secondary injection into the furnace of the boiler.

TABLE I
CHARACTERISTICS OF THE PELLETS USED IN THE EXPERIMENTS

Parameter	Value	Unit
Ash content	0,78	w-%, dry
Moisture content	6,10	w-%
Net calorific value	17,55	MJ/kg
Gross calorific value	18,90	MJ/kg
Bulk density	609	kg/m^3
Fines	0,5	w-%
Mechanical durability	96,4	%

A. Secondary air injection

Supplementary air for the combustion process is injected separately from the primary air injection into the upper zone of the flame or after it. In this experiment a secondary air injection was conducted in the upper zone of the flame through the steel ring with nozzles placed into the furnace. The ring was fixed in the centre of the furnace 5 cm above a burner cone and approximately 20 cm above the fuel bed (see Fig. 8). The secondary air was delivered up until the ring from the bottom of furnace through a steel pipe. Air was delivered into the furnace with the help of ca ompressor (without an oiling system) with a regular flow and pressure of < 0.2 bar.

The first boiler tests showed that flame was distributed and turned down already in the middle of the furnace. As a result, the ring was placed above the burner cone to exclude distribution of the flame prolonging a length of the combustion zone

and injecting additional air into the upper zone of the flame. Three variations of the nozzle placement were examined: horizontal (a), vertical (b) and spiral (c) (see Fig. 9).

tors did not produce the results desired because of the excess of boiler and funnel nominal flow, which created overpressure in the furnace as a result.
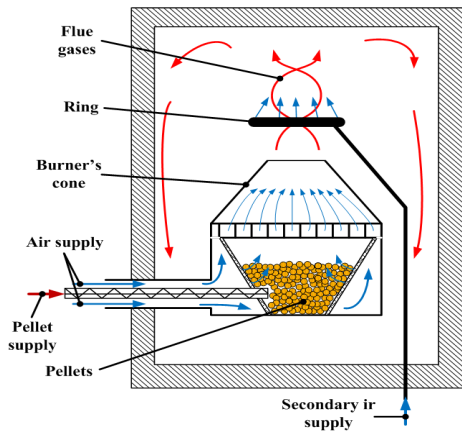

Fig. 8. Scheme of boiler furnace with a ring for secondary air injection.
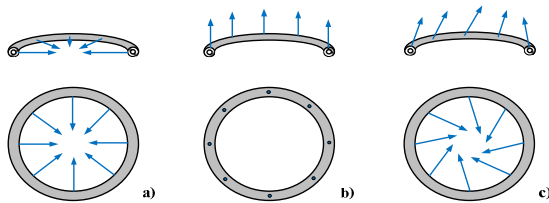

Fig. 9. Examined variations of the air nozzle.

Initially, the variant with horizontally-placed nozzles and air injection parallel to the flame was examined (a). This type of air injection made a distribution of the flame even stronger and it was not investigated further. The vertical nozzle placement (air injection parallel to the flame) lengthened the flame but more noticeable effect was achieved with spiral nozzle placement at 30°. This type of nozzle placement made it possible to lengthen the flame thereby intensifying a spiral effect of it turning. Two full time tests of boilers were performed using the ring with transversally placed nozzles.

B. Flue gas recirculation

To conduct the experiments, flue gas recirculation was performed draining a part of the flue gas into the air injection channel (see Fig. 10). Recirculation was ensured with the help of a centrifugal ventilator and for the regulation of recirculation level a speed of rotation of the ventilator driving motor was changed.

The flue gas drained from the funnel was delivered to the air injection channel where it was mixed with air delivered to the combustion process. Actually this solution is a formation of air-flue gas mixture and injection into the boiler furnace.

Using the flue gas recirculation principle mentioned above, several pilot tests and one full-time test were performed. During the tests it was established that flue gas recirculation in the air injection system substantially impacts its productivity. As a result, a lack of air necessary for combustion was observed. However, enhancing the productivity of the air injection ventilator at the level of recirculation was diminished. The simultaneous increase of both ventila-
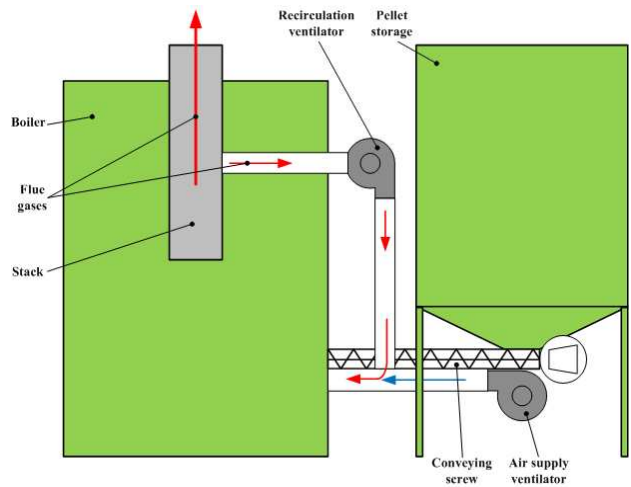

Fig. 10. Principal scheme of flue gas recirculation (view from behind).

For the performance of the full-time test, the mentioned recirculation system productivity of both ventilators was maintained at a level to ensure minimal flue gas recirculation and the air amount necessary for combustion.

To avoid an impact of air injection and flue gas recirculation system for the performance of further experiments, flue gas recirculation was performed injecting flue gas directly into the burner (see Fig. 11). A pipe was connected to the ventilator of recirculation and flue gas was delivered through this pipe to the burner. Flue gas was injected into the centre of the burner slightly above the pellet level.

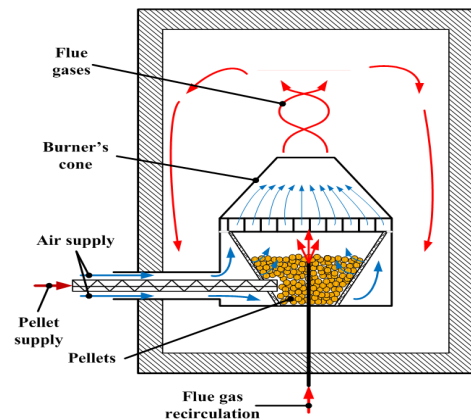Fig.11. A scheme of boiler furnace with a flue gas injection into the burner from the bottom.

Using the flue gas recirculation system mentioned above, several pilot tests and one full-time test were performed.

VI. TEST RESULTS

During the research five full-time boiler tests were performed: one reference test and four tests with different technical solutions. For further reference there is a letter assigned for each test:

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A. Reference test, without changes in boiler construction;
B. Flue gas recirculation through the air injection system;
C. Secondary air injection into the furnace through the ring;
D. Flue gas recirculation through the air injection system

and secondary air injection through the ring;
E. Flue gas recirculation directly into the boiler burner.

The results of measurements of the flue gas monitoring, flame temperature and boiler performance efficiency performed during the tests are summarized in Table 2.

TABLE II

RESULTS OF BOILER TESTS

Test	O_2, %	CO_2, %	CO, ppm	NO, ppm	CO at 10% O_2, mg/nm^3	NO_x at 10% O_2, mg/nm^3	Flue gas temp., ºC	Flame temp., ºC	PM at 10% O_2, mg/ Nm^3	η, %
A	9.28	10.8	177	112.4	288.6	196.3	106.3	808.8	27.9	87.1
B	6.75	12.9	312	124.0	418.7	178.3	106.6	810.7	59.3	86.5
C	8.43	12.0	111	124.5	165.0	198.0	96.8	833.3	28.8	88.9
D	5.67	14.7	827	123.3	1028.3	172.7	105.3	776.0	20.6	84.8
E	6.47	13.8	882	114.6	1105.5	154.5	88.8	858.2	18.4	87.5

A comparison in the fluctuations of concentrations of NO_x emissions in the five tests performed is shown in Figure 12. Changes of concentrations given in the diagram refer to normal conditions with an oxygen concentration 10%-vol and characterizes changes of concentrations within two hours in the middle of the test.
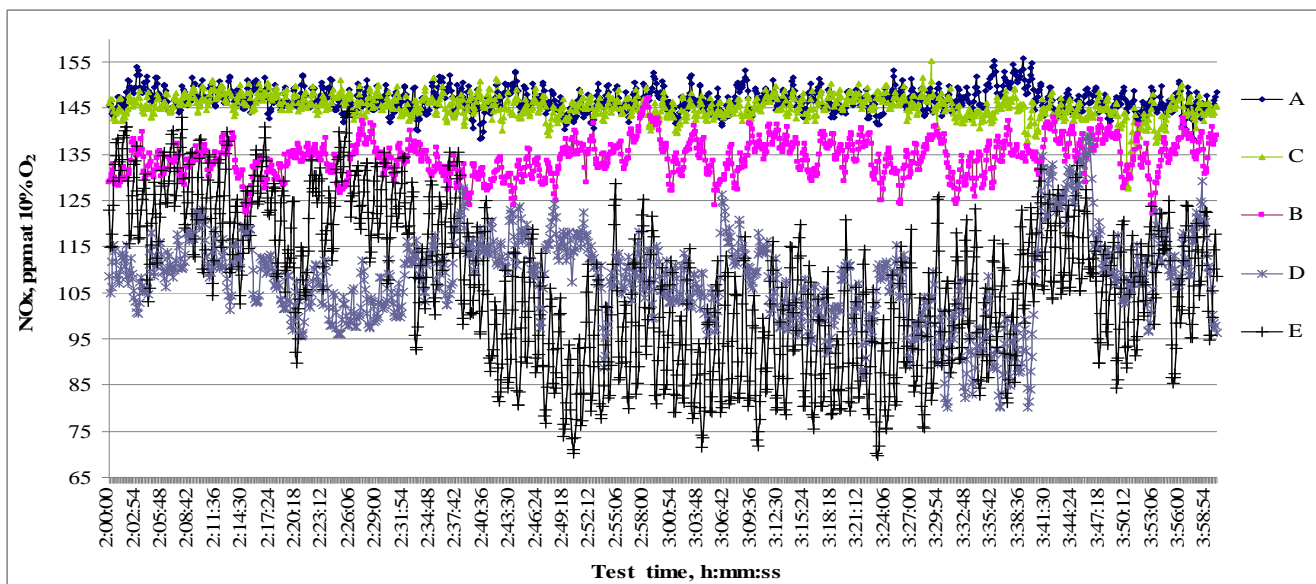

Fig. 12. Comparison of fluctuations of concentration of NO_x emissions.

VII. CONCLUSIONS

Secondary air injection in the upper part of the flame does not impact the formation of NO_x but instead a reduction of CO was observed. Spiral placement of nozzles in the steel ring helps to avoid flame scattering and lengthens the zone of combustion. A further investigation of this solution can offer a reduction of carbon monoxide emissions. The secondary air supply system used in the experiments is not sufficient to decrease primary air supply below α ≈ 0.7. Therefore no impact on the NO_x concentration level was observed using this system.

From the NO_x emission reduction point of view, a flue gas recirculation has greater potential. The recirculation

was used during three tests and results of those tests showed reduction of NO_x emissions, but an essential increase of CO. For further use of flue gas recirculation, it is necessary to optimize the amount of supplied air along with the use of complete combustion methods;

Flue gas recirculation through the air injection system is not technically correct and it is hard to apply. This method does not offer preferable flue gas recirculation because ventilators of air injection and recirculation mutually impact the performances of each other. Flue gas recirculation through the air injection system is connected also with the possible inflow of flue gas into the area through the air ventilator, formation of condensation in the air injection channel and problems with regulating the performance of both ventilators;

The highest NO_x emissions reduction was achieved using flue gas recirculation with delivery through the bottom of the burner into the centre of the flame. Further research of this method is required using mechanisms for carbon monoxide reduction in parallel;

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Aivars Žandeckis, Dagnija Blumberga, Claudio Rochas, Ivars Veidenbergs, Kaspars Siliņš. Slāpekļa oksīdu samazināšanas metodes granulu katlos

Biomasas dedzināšana ir saistīta ar augstām NO_x emisijām, jo kurināmajam ir augsts slāpekļa saturs. Pastāv vairāki slāpekļa oksīdu veidošanās mehānismi, bet eksperimentālie pētījumi pierāda, ka biomasas degšanas procesā nozīmīgs ir tikai kurināmā-NO mehānisms. Eksistē vairākas NO_x emisiju samazināšanas metodes, bet pārsvarā tās tiek pielietotas lielas jaudas rūpnieciskajos katlos.

Šī pētījuma galvenais mērķis bija izveidot un izmēģināt tehniskos risinājumus slāpekļa oksīdu emisiju samazināšanai nelielas jaudas granulu katlā. Pētījumā tika izmantots Latvijā ražots granulu apkures katls ar nominālo jaudu 15 kW, eksperimentu veikšanai tika izmantotas kokskaidu granulas. Izmēģinātas divas NO_x emisiju samazināšanas metodes: sekundārā gaisa padeve kurtuvē un dūmgāzu recirkulācija. Sekundārā gaisa padeve tika nodrošināta caur kurtuvē ievietoto gredzenu padodot gaisu liesmā 5 cm augstumā virs degļa konusa. Tika pārbaudīti gredzeni ar sprauslu trīs izvietošanas variantiem: horizontālo, vertikālo un spirālveidīgo. Gredzena izmantošanas mērķis bija pagarināt reakcijas zonas garumu, nepieļaujot liesmas izkliedi kurtuves vidusdaļā. Šo vēlamo rezultātu izdevās sasniegt tikai ar spirālveidīgi izvietotām gaisa sprauslām. Šajā pētījumā tika pārbaudīti divi recirkulētu dūmgāzu padošanas veidi. Viens ir recirkulēto dūmgāzu sākotnēja sajaukšana ar degšanai padodamo gaisu un ievadīšana deglī. Otrs ir dūmgāzu padošana tieši liesmā caur deglī no apakšas ievietoto cauruli. Tika pārbaudīta arī kombinētā metode, kad tiek padots gan sekundārais gaiss, gan recirkulētās dūmgāzes. Tika noskaidrots, ka sekundārā gaisa padošanas metode nesniedz NO_x samazinājumu. Dūmgāzu recirkulācijas metodes sniedza NO_x emisiju samazinājumu līdz pat 21%. Šāda apjoma samazinājums tika panākts, padodot recirkulētās dūmgāzes tieši liesmā caur degļa apakšdaļu.

Айварс Жандецкис, Дагния Блумберга, Клаудио Роша, Иварс Вейденбергс, Каспарс Силиньш. Метод сокращения оксидов азота в гранульных котлах

В процессе горения биомассы образуются повышенные выбросы оксидов азота, что вызвано высоким содержанием азота в топливе. Существует несколько механизмов образования оксидов азота, но экспериментальные исследования показывают, что при горении биомассы значительным является только механизм образования топливных NO_X. Существует несколько методов снижения выбросов NO_X, но обычно они применяются в промышленных котлах большой мощности.

Целью данного исследования являлось создание и испытание технических решений по снижению выбросов NO_X в гранульном котле малой мощности. В исследовании использовался произведенный в Латвии гранульный котёл мощностью 15 кВт, в качестве топлива были выбраны гранулы из древесной стружки. В ходе исследования были использованы два метода снижения выбросов NOx: двухступенчатая подача воздуха в топку и рециркуляция дымовых газов. Двухступенчатая подача воздуха осуществлялась через размещенное в топке кольцо. Воздух подавался в пламя на высоте 5 см от конуса горелки. Были проверены кольца с горизонтальным, вертикальным и спиральным расположением воздушных сопел. Кольцо использовалось для продления зоны реакции и предотвращения рассеивания пламени в середине топки. Желаемый результат был достигнут только в случае использования спирально расположенных сопел. В исследовании были опробованы два метода подачи рециркулированного дыма. Первый метод заключался в предварительном смешивании дыма с подаваемым в топку воздухом. Второй метод основывался на подаче дыма прямо в пламя через трубку, размещённую внизу горелки. Был проверен и комбинированный метод с двухступенчатой подачей воздуха и рециркуляцией дыма. Было установлено, что примененный метод двухступенчатой подачи воздуха не даёт снижения NO_x. Рециркуляция дыма позволила снизить выбросы NO_X до 21%. Самый высокий результат был достигнут при подаче дыма напрямую в пламя через нижнюю часть горелки.