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The Method of Nitrogen Oxide Emission Reduction During the Combustion of Gaseous Fuel in Municipal Thermal Power Boilers

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1. Introduction

Currently, the Polish heat management works mainly on solid fuel (Konieczyński et al. 2017, Man et al. 2005, Park et al. 2013). Such a policy causes more and more technical, economic and ecological problems due to the conditions set for us by the European Union countries (Szyszlak-Bargłowicz et al. 2015, Szyszlak-Bargłowicz et al. 2017, Zając et al. 2017). Recently, the Polish government announced the country's heat policy program in the perspective of 2040. It assumes, among others transition of heat management from solid fuel to natural gas. Therefore, the challenge for Polish heating is the effective and environmentally friendly transition (switching) of thermal energy from solid fuel to gaseous fuel. These are devices called "Low energy" due to their age are characterized by low efficiency and a significant impact on the level of environmental pollution in the ground layers of the atmosphere (Zandeckis et al. 2010, Zang et al. 2015). The exhaust gas from these devices is discharged into urban development zones through small chimneys. The EU regulations obliging all European Union countries, including Poland, to reduce greenhouse gas emissions are not without significance here.

The combustion of organic fuel is accompanied by the formation and emission of toxic and carcinogenic substances into the atmosphere. In addition to nitric oxide, exhaust gases may contain carbon monoxide, aldehydes, organic acids and other carcinogenic compounds. The harmful importance of these pollutants for the natural environment is emphasized by the fact that they are legally limited. The emission of nitrogen oxides or dust depends on the type of fuel burned (Dal Secco et al. 2015, Xu et al. 1999, Wilk et al. 2010). Each of these substances has a different quantitative composition and poses a different danger to man and the environment. During the combustion processes, the construction details and technological conditions affect the concentration of harmful components contained in the exhaust gas to varying degrees. For example, when burning gaseous fuel containing no sulfur, the emission levels of harmful substances contained in the exhaust gas are as follows (Sigal 1988):

- benzo(a)pyrene 0-20 μg/100 m^3,
- carbon monoxide 70-100 mg/m^3,
- sulphur dioxide 0 mg/m^3,
- nitrogen oxides 100-400 mg/m^3.

The above statement shows that mainly oxide and nitrogen dioxide (NO_x) determine the level of environmental performance of boiler equipment when burning gaseous fuel (Kromilitsyn & Ezhov 2013, Szkarowski & Janta-Lipińska 2011, Szkarowski & Janta-Lipińska 2013, Szkarowski & Janta-Lipińska 2015).

2. Formation mechanisms and methods for the suppression of nitrogen oxides

The concentration of nitrogen oxides in the exhaust gas depends on the maximum temperature of the combustion process, the concentration of oxygen in the combustion zone, the residence time of the reacting mixture in the maximum temperature zone, and on the nitrogen content in the fuel. Depending on the combination of these parameters, NO_x emissions in flue gas may oscillate from 0.1 to 2.0 g/m^3.

In the literature there are three mechanisms for the formation of nitrogen oxides in a flame of burning fuel distinguished (Gradoń 2003, Zeldovich 1946):

- thermal – which is formed as a result of high temperature oxidation of nitrogen from the air,
- prompt – formed in the initial combustion zone by chemical reactions with the participation of CH and CH_2 radicals. There is also a known in the literature hypothesis regarding another possible mechanism for the formation of nitrogen oxides in an organic fuel flame (the so-called "impact"), which otherwise explains the difference between the content of nitrogen oxides and the thermal mechanism of their formation (Szkarowski 2014),
- fuel – produced with the participation of chemical compounds containing nitrogen and included in the fuel.

Figure 1 shows a diagram of the formation of nitrogen oxides in the range of temperatures characteristic of boiler furnaces. In some cases, the formation of nitrogen oxides occurs predominantly by one of three mechanisms. For example, when burning gas in low-power devices, the so-called "prompt" NO_x prevail, wheras in fluidized coal combustion the "fuel" ones. The combustion of gaseous fuel in the furnaces of boilers is accompanied by the formation of thermal and prompt nitrogen oxides.

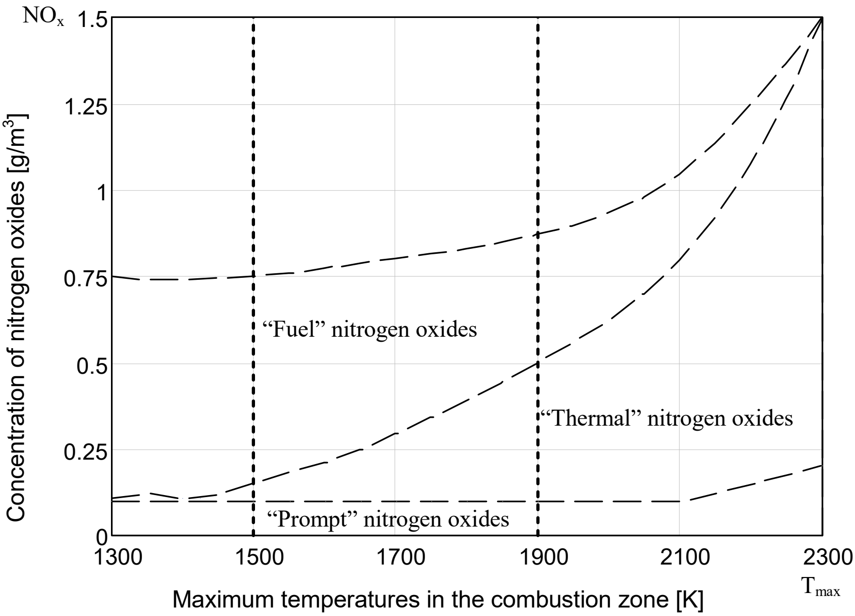

Fig. 1. Dependences of the concentration of nitrogen oxides, as a function of maximum temperatures in the combustion zone, divided into characteristic zones of the influence of NO_x formation mechanisms

The main directions of research in the field of suppressing nitrogen oxide emissions, taking into account the thermal mechanism of their formation, was the reduction of the maximum temperature and oxygen concentration in the combustion zone.

This can be achieved by:

- combustion with reduced α,
- exhaust gas recirculation,
- moisture injection (Janta-Lipińska &Shkarovskiy 2020a),
- multistage combustion.

Author in the composition of an international research team headed by prof. Szkarowski has been involved in the use of combustion methods with reduced α and moisture injection for many years. It should be emphasized that these two ways often complement each other. This article summarizes a number of experimental and theoretical studies in these two methods (Janta-Lipińska & Szkarowski 2018, Szkarowski 2002, Szkarowski & Janta-Lipińska 2009, Szkarowski & Janta-Lipińska 2011, Szkarowski & Janta-Lipińska 2013).

3. Theoretical research

The method of water ballast injection is considered one of the most promising scientific and technical solutions aimed at reducing atmospheric pollution by harmful products of organic fuel combustion (Szkarowski 2002, Szkarowski 2003, Szkarowski et al. 2016, Szkarowski et al. 2018, Janta-Lipińska & Shkarovskiy 2020a). Compared to other atmosphere protection technologies, the injection method is characterized by unique energy-ecological and technical-economic indicators (Jemieljanow 1992, Palenko et al. 2014).

As a result of the conducted research, the following two issues were analyzed. The first of these was to determine the detailed structure of the flame in terms of the processes of nitrogen oxides (NO_x) production that occur. This was to ensure optimal ballasting of the zones where the processes take place (Herdzik & Noch 2018). The second issue was to explore the possibility of intensifying processes within the flame to maximize the reduction of the excess air supplied for combustion and to reduce the value of heat loss with exhaust gases.

I.J. Sigal divided the combustion process into four temperature zones (Sigal 1988) that determine the formation of nitrogen oxides (Fig. 2). Zone I is the zone where the maximum temperature in the combustion zone reaches up to 750K. In turn, zone IV is the maximum temperature in the combustion zone reaching the limit above 2500K. The author of this division recognized that for the processes occurring in the furnaces of boilers, the temperature conditions of the zones occurring in the so-called III a and III b zone are characteristic.

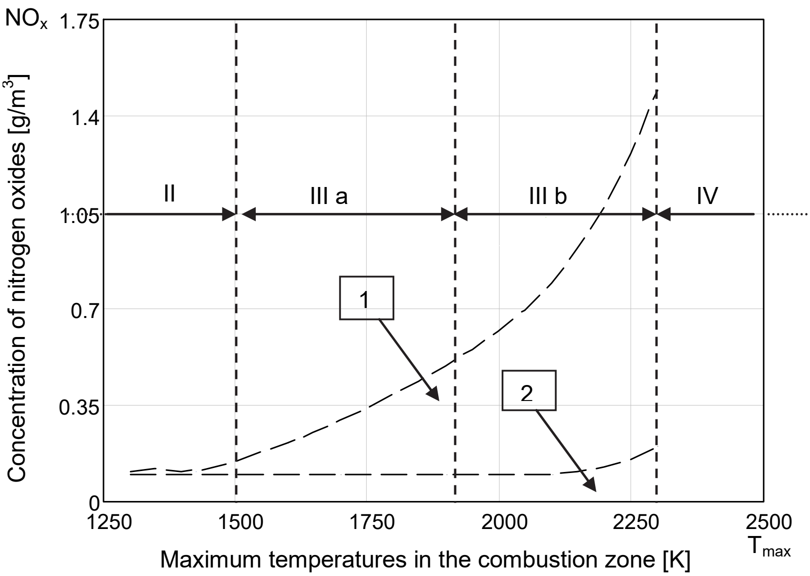

Fig. 2. Dependences of the concentration of nitrogen oxides as a function of maximum temperatures in the combustion zone, divided into zones of influence according to Sigal

Another division was proposed by L.M. Tsyrulnikow, namely the division of the flame structure into four zones depending on the relative length of the flame (Tsyrulnikow 1980) (Fig. 3):

- zone A_1 – from the place of flame outlet from the cross section of the burner to the cross section of the furnace where the temperature is 1650K (it is the temperature at which the concentration of thermal nitrogen oxides reaches the value of 1 mg/m^3),
- zone A_2 – from the above-mentioned section to the place where the maximum temperature in the flame is obtained, where the intensity of nitrogen oxidation from air reaches a maximum,
- zone B – from the cross-section with the maximum temperature in the combustion zone to the cross-section with the "critical" temperature of 1650K, where combustion of combustible components usually ends, and the concentration of "air" NO_x reaches its maximum value,
- zone C – from the section mentioned above to the exit from the furnace, where there are no significant changes in the concentration of nitrogen oxides.

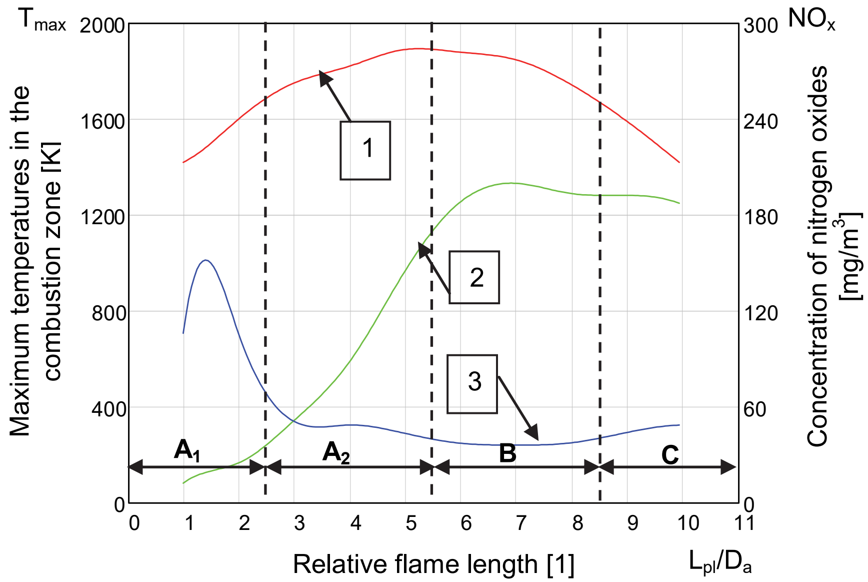

Fig. 3. Dependences of the maximum temperature in the combustion zone (1) and concentration of nitrogen oxides (2-thermal, 3-prompt) in flame as a function of relative flame length

On the other hand A.A. Jemieljanow distinguishes, in the resulting flame, the zones of intensive generation of nitrogen oxides (ZIG) (Jemieljanow 1992). The zones he separates are treated as intervals for achieving local temperature maxima.

The author has attempted to jointly consider and mutually enrich the flame structure analysis proposed by Sigal, Tsyrulnikow and Jemieljonow. This allowed to formulate the concept and separate two zones of decisive influence (ZDI), which determine the possibility of active influence on various processes occurring in the flame, also the mechanisms of nitrogen oxide formation:

- ZDI-I-, which includes a significant part of zone A_1, in which by introducing water ballast you can control the processes taking place in this flame zone in order to affect the conditions determining the intensity of further NO_x production by non-thermal mechanisms of its formation (i.e. prompt, impact).
- ZDI-II- is the zone of maximum temperatures at the junction of zones A_2 and B, in which both ballasting and controlling the excess air coefficient enables throttling of the thermal mechanism of nitrogen oxidation. An overview diagram of the flame as a result of such analysis is shown in Fig. 4.

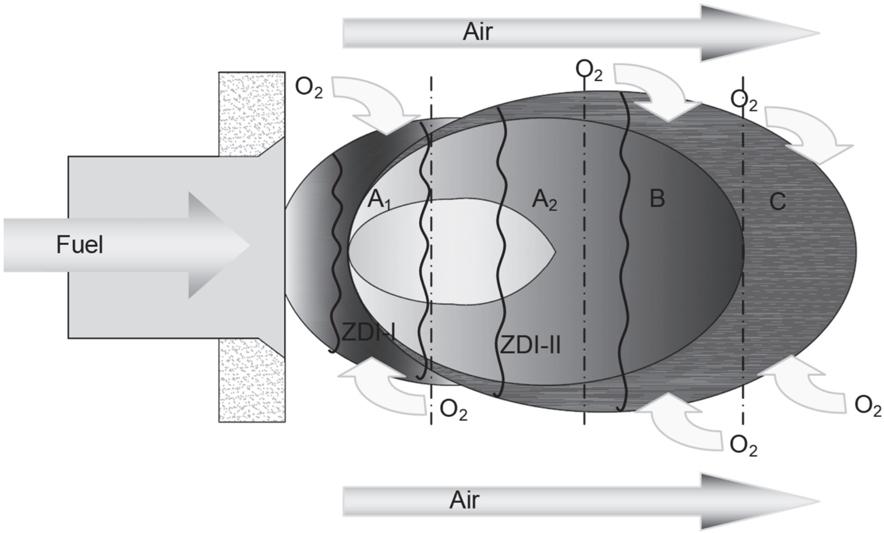

Fig. 4. Schematic diagram of the structure of the flame divided into zones of decisive influence

Studies on reducing NO_x emissions are usually based on the structure of the flame in its entirety (Sigal 1988, Tsyrulnikow 1980, Jemieljanow 1992) with the separation of the flame nucleus and other parts thereof. The measures taken to reduce the intensity of NO_x formation anticipate the effect on the entire flame. Known methods for reducing NO_x emissions (Krawczyk 2016, Kropka 2010, Lee et al. 2006, Janta-Lipińska & Szkarowski 2018, Xue et al. 2009) developed on this basis include: humidifying the entire air stream in front of the burner or ballasting it with exhaust gases. Some achievements of such methods are indisputable but limited.

However, the majority of the currently produced burners are characterized by turbulent-diffusion combustion organization (Gradoń 2003). The flame in the burner tunnel and then in the furnace is not uniform. It consists of many individual and in some sense isolated structures. Each fuel stream, mixing with the air flowing into it, creates such a structure (in aerodynamic and thermodynamic terms). The combination of mutually building up structures constituting molar masses of burning fuel can be defined as mono-flame, micro-flame, partial or component flames. Each mono flame is a fairly determinate structure that reacts only with the surrounding air stream. In a simplified form, not taking into account the turbulence of flame, Fig. 5 shows the aforementioned flame division zones and ZDI-s occurring in each monoflow (Szkarowski 2002).

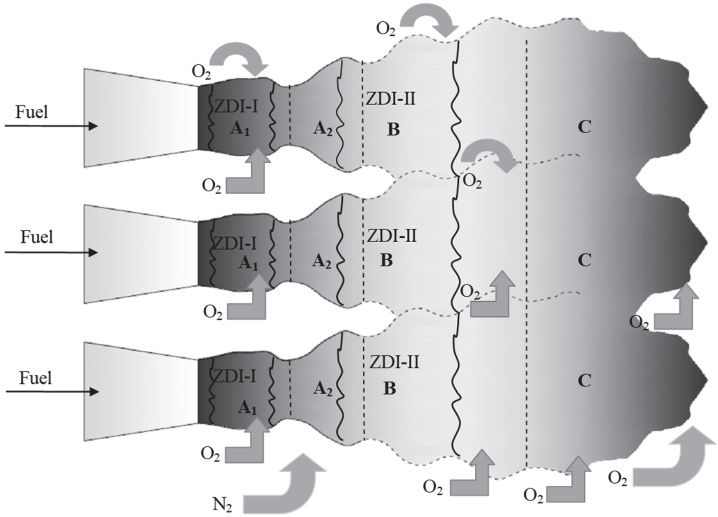

Fig. 5. Schematic diagram of the structure of a turbulent multi-stream flame

The mono-flames retain their seclusion until the beginning of zone B. That is in zones ZDI-I and ZDI-II. The end of zone B and the entire zone C are characterized by a quick connection of mono-flames and the formation of a more uniform structure of the entire flame. From this point of view, the generally accepted principle of examining the flame in its entirety is contrary to the complex structure of the flame described above. The course of the processes of formation and combustion of nitrogen oxides in each mono-flame is somewhat independent. Based on the above premises, a method of impact on the ZDI was proposed in each mono-flame. Experimental verification of these assumptions took place directly on steam boilers in operating boiler room conditions.

4. Research objects

The tests were carried out on four steam boilers of different power: DKVR 10-13, DKVR 20-13, DE 25-14 and PTVM-50 (Janta-Lipińska &Shkarovskiy 2020b). Each of the tested boilers was in a different industrial and heating boiler room located in the St.-Petersburg district. All tested boilers operated on gaseous fuel. Characteristics of individual boilers are presented in Table 1.

Table 1. List of boilers parameter values, on which investigations have been performed

Parameter	Boiler type			
	DKVR10-13	DKVR20-13	DE 25-14	PTVM-50
Boiler heat power [MW]	8.37	14.09	14.91	53.78
Type of burner	GMG-5.5	GMGB-5.6	GMP-16	DKZ
Number of burners	2	3	1	12
The fan and exhaust installation				
- Blow fan	VD-8	VD-10	VD-10	WC-14-46-8
- Exhaust fan	D-10	D-10	D-13.5	–

Based on the theoretical assumptions made above and the preliminary analysis of the flame structure by means of simulation and photography methods, individual constructions of moisture injection heads were developed for each boiler and burner. To ensure proper supply of water ballast to the ZDI-I and ZDI-II zones, the number of holes, their location and angle of inclination were subjected to each mono flame. During the tests, the pressure of injected steam was an additional factor. In the case of multi-burner boiler designs (i.e. PTVM-50 with 12 burners), parameters in different rows of burners were also differentiated. An example of such a head for the GMP-16 burner of the DE 25-14 boiler is shown in Fig. 6. The design of the head provided intensive mechanical and chemical interaction in the ZDI-I zone in the mono-flame of each gas stream. The rest of the water ballast provided interaction in ZDI-II by dissociation of water vapor. This principle of active impact on ZDI in each mono-flame has been referred to as directed dosed steam ballasting.

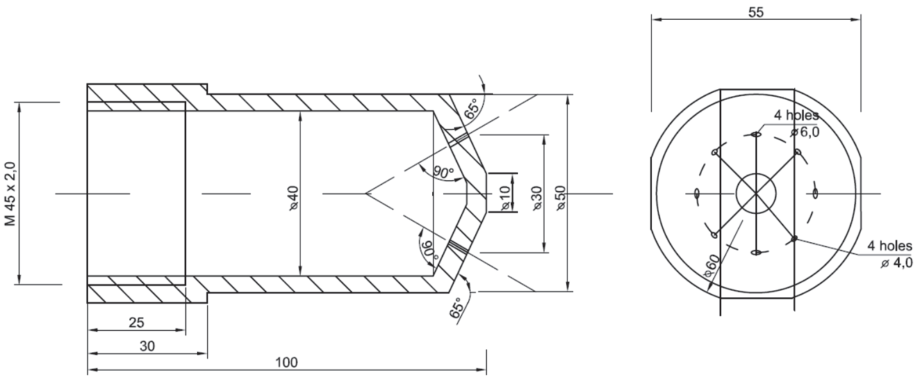

Fig. 6. Technical drawing of the exemplary design of the head for injecting moisture into the zones of decisive influence for the DE 25-14 boiler with the GMP-16 burner

5. Experimental results

The investigations have been performed on four gas-fired boilers. The performed investigations allowed to achieve the best results of the use of the proposed method with an inject of the moisture into zones of decisive influence (ZDI-I and ZDI-II).

In Fig. 7 the mass emission of nitrogen oxides as a function of boiler efficiency for two modes of its operation has been presented. The first mode relies on the measurements of mass emissions of nitrogen oxides during boiler work under its actual operating conditions, while the second one relies on the measurements with the additional suppression system of oxide emissions on (Shkarovskiy et al. 2016). In both cases, the value of the emission of nitrogen oxides depends on the boiler's steam capacity or its thermal power. The higher the steam output of the boiler or its heat output, the greater the mass emission of nitrogen oxides.

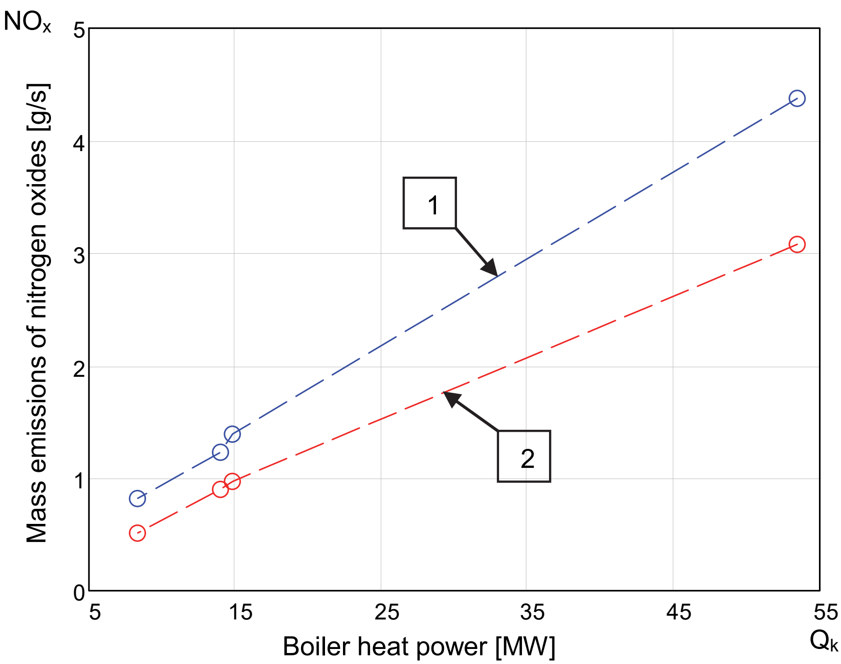

Fig. 7. The dependences of mass emission of nitrogen oxides as a function of boiler heat power (1 – boiler without additional systems activated; 2 – boiler with activated system of suppressing nitrogen oxides emission)

In Fig. 8 the obtained results of the mass value of nitrogen oxides emission, calculated to 1 MW heat power, for two boiler modes have been presented. This figure presents the effectiveness of the directed metered flame ballast method. The characteristics presents that the specific mass emissions of nitrogen oxides are lower for boilers with maximum power with the system turned on than for boilers with the minimum power in normal operating modes (without the NO_x suppression system switched on). The application of an automatic suppression system of nitrogen oxides emission on each of the boilers allowed reducing this emission by average 30%. In the case of the DKVR 10-13 boiler, compared to the value obtained for actual operating conditions, the reduction in nitrogen oxide emissions reached 37%. The steam consumption per flame injection for each of the investigated boilers has been presented in Fig. 9. In each case, the steam consumption per injection did not exceed 1% of the steam capacity of the boiler or its heat output (Janta-Lipińska & Shkarovskiy 2020a). The increase of boiler efficiency, being a result of the use of the proposed method, compensated the steam consumption per injection.

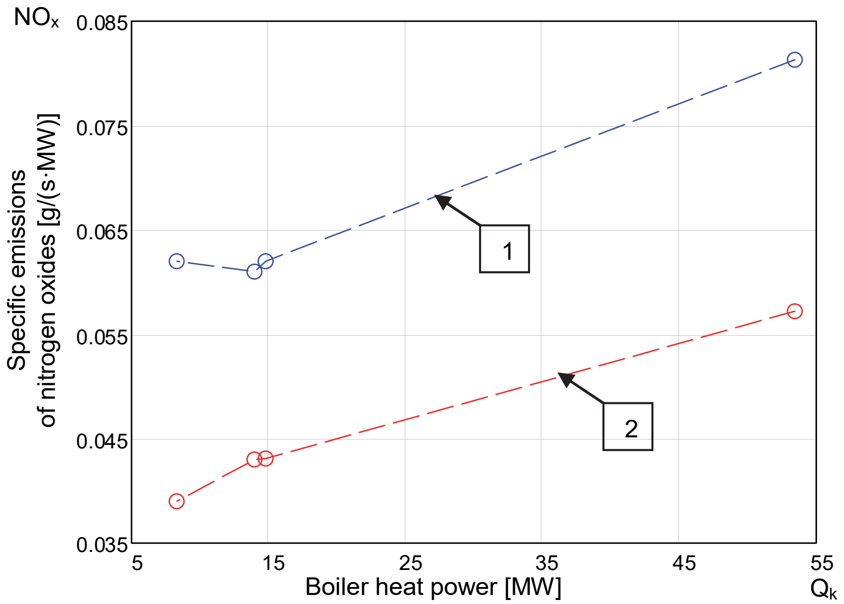

Fig. 8. Dependences of specific emissions of nitrogen oxides as a function of boiler heat power (1 – boiler without additional systems activated; 2 – boiler with activated system of suppressing nitrogen oxides emission)

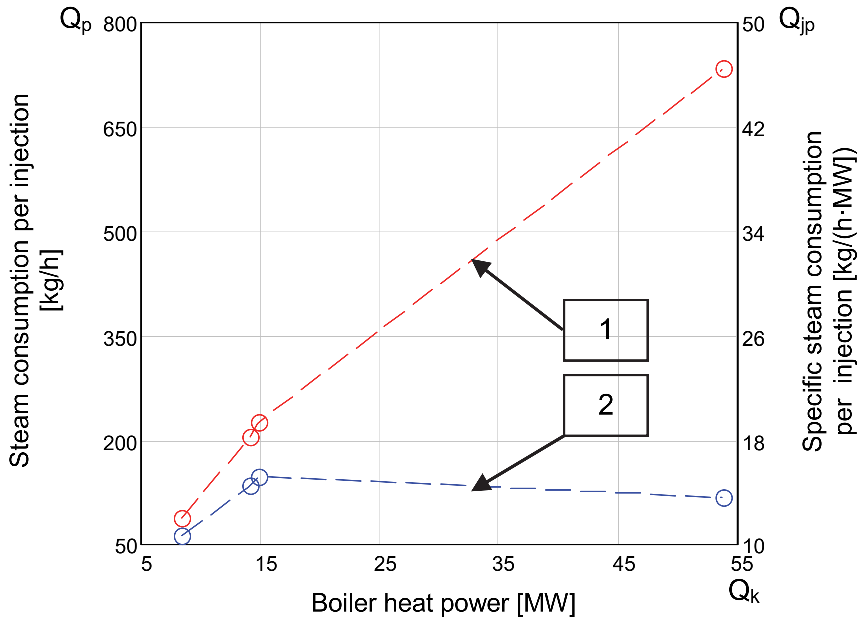

Fig. 9. The dependences of steam consumption (1 – absolute, 2 – unit) per injection as a function of boiler heat power (1 – absolute, 2 – unit)

6. Conclusions

1. A method for reducing nitrogen oxide emissions in city heat boilers has been developed and proposed. The method relies in directing the dosed moisture injection into the flame zone.
2. The method has been experimentally verified on steam and water thermal power boilers with capacities from 8.37 to 53.79 MW. The number of the burners in these boilers was form 1 to 12.
3. It has been proved that the proposed method allows a reduction of nitrogen oxides by 30-40% with moisture injection not exceeding 0.9% of the boiler efficiency. Due the work of a boiler with moisture injection is accompanied by an increase in its efficiency to 1%, the use of the proposed method does not reduce the efficiency of fuel consumption in the heat source.

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Abstract

The nitrogen oxides in a flame of burning fuel can be created by many mechanisms. The amount of NO_x concentration emitted to the ground atmosphere mainly depends on the type of fuel burned in the industrial and heating boilers. Changes in the country's thermal policy and requirements that are set for us by the European Union States are forcing us to reduce greenhouse gas emissions. Directed metered ballast method is one of the most attractive techniques for reducing NO_x emissions. In recent years, moisture injection technology is still investigated on low and medium power thermal power boilers operating on gaseous fuel. The goal of this work was to perform the investigations of the process of a moisture injection into the zones of decisive influence (ZDI-I and ZDI-II) on steam and water boilers: DKVR 10-13, DKVR 20-13, DE 25-14 and PTVM-50. The obtained results clearly show how the proposed method affects NO_x reduction and boiler efficiency.

Keywords:
emission, combustion, dosed directional ballasting method, mono flame, nitrogen oxides

Metoda zmniejszenia emisji tlenków azotu przy spalaniu paliwa gazowego w kotłach miejskiej energetyki cieplnej

Streszczenie

Tlenki azotu w płomieniu palącego się paliwa mogą powstawać na drodze wielu mechanizmów. Ilość emitowanego do przyziemnej warstwy atmosfery stężenia NO_x wynika przede wszystkim z rodzaju spalanego w kotłach przemysłowo-grzewczych paliwa. Zmiany w polityce cieplnej kraju oraz wymagania stawiane nam przez Państwa Unii Europejskiej zmuszają na do zmniejszenia emisji gazów cieplarnianych. Metoda skierowanego dozowanego balastowania jest jedną z najbardziej atrakcyjnych technik ograniczania emisji NO_x. W ostatnich kilku latach technologia wtrysku wilgoci badana jest na kotłach energetyki cieplnej małej i średniej mocy pracujących na paliwie gazowym. Celem pracy są badania eksperymentalne procesu wtrysku wilgoci do stref decydującego wpływu (ang. zone of decisive influence ZDI-I oraz ZDI-II) na kotłach parowych i wodnych: DKVR 10-13, DKVR 20-13, DE 25-14 oraz PTVM-50. Uzyskane wyniki pokazują, w jaki sposób proponowana metoda wpływa na redukcję NO_x oraz wydajność.

Słowa kluczowe:
emisja, spalanie, metoda skierowanego dozowanego balastowania, mono-płomień, tlenki azotu