www.czasopisma.pan.pl PAN www.journals.pan.pl

Archives of Environmental Protection
Vol. 46 no. 2 pp. 100–107

PL ISSN 2083-4772
DOI 10.24425/aep.2020.133480

Investigations of nitric oxides reduction in industrial-heating boilers with the use of the steam injection method

Sylwia Janta-Lipińska[1], Alexander Shkarovskiy[1,2]*

[1]Koszalin University of Technology, Faculty of Civil Engineering, Environmental and Geodetic Sciences, Poland
[2]Saint Petersburg State University of Architecture and Civil Engineering,
Faculty of Environmental Engineering and Municipal Services, Russia

* Corresponding authors e-mail: alexander.shkarovskiy@tu.koszalin.pl

Keywords: environmental protection, nitric oxide, emission levels, industrial gas boilers, emission reductions.

Abstract: This article presents results of research concerning the possibility of reducing the level of toxic nitric oxides (NO_x) emission to the atmosphere. The research has been conducted on DKVR 20-13, PTVM-50 and DE 25-14 gas boilers. The complex character of this issue requires individual consideration regarding each boiler configuration. Each case requires consideration of characteristics and details of all elements constituting the boiler-furnace unit. The main problem was to establish the reference level to which the reduction of nitric oxides occurs. The actual maximum emission of nitric oxides was assumed as this level. It was verified with the maximum allowable emission of nitric oxides for each boiler. Three levels of the potential influence of emission on the atmosphere have been taken into account. This experimental research allowed for proposing an effective method, which led to reducing nitric oxides emission by around 30%.

Introduction

The nitric oxides reduction still is a complex and important problem. The nitric oxides are current issue which is in a wide range of interest of many investigators (Zhang et al. 2015, Xu et al. 1999, Man et al. 2005, Park et al. 2013, Xue et al. 2009, Krawczyk 2016, Dubois and Boutin 2018, Juściński 2018, Jurik et al. 2017, Konieczyński et al. 2017, Strelets and Vatin 2015). In this paper we present results of the research concerning the possibility of reducing toxic nitric oxides (NO_x) emission to the atmosphere. Experimental results have been performed on DKVR 20-13 (Szkarowski and Janta-Lipińska 2011, Szkarowski and Janta-Lipińska 2013, Szkarowski and Janta-Lipińska 2015, Szkarowski et al. 2016), PTVM-50 and DE 25-14 gas boilers. The number of steam boilers, type DKVR, PTVM and DE, with the capacity of up to 50 t/h, being in use, is estimated in tens of thousands. Currently, these boilers are still produced. One of the reasons for their popularity is the unique range of power regulation, from 50% up to 100% (in the case of DKVR boilers – up to 140%). The aim of the conducted research was to create and implement a method that would reduce the emission of nitric oxides to the atmosphere for DKVR 20-13, PTVM-50 and DE 25-14 boilers. The boilers, on which the research was conducted, were located in three Sankt Petersburg boiler plants (Szkarowski and Janta-Lipińska 2011, Szkarowski and Janta-Lipińska 2013, Szkarowski and Janta-Lipińska 2015, Szkarowski et al. 2016, Janta-Lipińska and Szkarowski 2018, Szkarowski and Janta-Lipińska 2009, Szkarowski et al. 2018).

This research assumed that the most effective ways of lowering NO_x emission to the atmosphere, are combined methods, which use different factors influencing intensity of its generation (Konieczyński et al. 2017, Janta-Lipińska and Szkarowski 2018, Collection of methods for calculating emissions of pollutants into the atmosphere by various industries 1986). Reduction of NO_x emission should not lower boilers efficiency and completeness of fuel burning products. Theoretical analysis and preliminary experimental research allowed to propose a method of steam injection into the combustion area (Pavlenko et al. 2014, Szkarowski 2001, Szkarowski 2002, Szkarowski 2003).

Research objects

The research was conducted in three different industrial-heating boiler plants, which are described below.

1. Boiler Plant S.A. Russkie Samocvety in Sankt Petersburg, where three DKVR 20-13 boilers were installed. They were dual-drum boilers with the vertical water pipe and the longitudinal location of the drums. Their nominal capacity was 20 t/h, with a possibility of 40% power excess. The maximum steam overpressure was 1.3 MPa. Each boiler was equipped

with three GMGB-5,6 gas-mazut burners (Szkarowski et al. 2018). The role of the burners is to burn low pressure natural gas. They were also equipped with mazut injectors, pulverizing it in the steam-mechanical method. Individual fan-ventilating installation of each boiler consisted of VD-10 blast fan and D-10 exhaustion fan. Each boiler was equipped with an individual economizer having heating area of 808 m^2. Exhaust gases were discharged to the atmosphere through a common chimney, made of brick, which has 1150 mm in diameter and is 45 m high. Table 1 shows values of fan parameters installed in S.A. Russkie Samocvety boiler plant in Sankt Petersburg.

2. Fourth Krasnovadyeska Boiler Plant in Sankt Petersburg equipped with two PTVM- 50 boilers, working directly for the purpose of the heating network. They were manufactured in the Czech Republic and their nominal power was 50 MW. This type of boilers has a shaft construction without draught regulators and their convection clusters are located directly above the shielded furnace. The boilers were equipped with 12 standard DKZ burners, placed in two blocks. These blocks were located on the opposite walls of the boiler. Each burner had its own WC 14-46-8 blast fan. Their goal was to burn natural gas, and they were equipped with mazut injectors pulverizing it mechanically. Table 2 presents values of parameters for fans installed in Fourth Krasnovadyeska Boiler Plant in Sankt Petersburg.

3. Kronshtadtskaja branch of GUP (National Unitary Company) "TEK SPB" (Fuel-Energetic Complex Sankt Petersburg) equipped with two DE-25-14 GM boilers. They are dual-drum boilers with the vertical water pipe and the longitudinal location of the drums. Their nominal capacity is 25 t/h, with a possibility of power excess up to 40%. The maximum steam overpressure was 1.3 MPa. Each boiler was equipped with GMP-16 gas-mazut burner. Their goal was to burn medium pressure natural gas, and they were equipped with mazut injectors, pulverizing it in the steam-mechanical method. The individual fan-ventilating installation of each boiler consisted of VD-10 blast fan and D-13-50 exhaustion fan. Table 3 presents values of parameters for fans installed in Kronshtadtskaja branch of GUP in Sankt Petersburg.

Operation of each boiler plant assumed use of mazut as an auxiliary fuel. Basing on the analysis of the technical documentation and the boilers' work card, it was established that mazut is used very rarely. The aim was to create and implement methods leading to the reduction of emission of nitric oxides (Strelets and Vatin 2015, Szyszlak-Bargłowicz et al. 2017, Szyszlak-Bargłowicz et al. 2015, Zając et al. 2017, Walery 2014) during gas burning (Kuropka 2010, Kormilitsyn and Ezhov 2013), with the possibility of switching to mazut burning on the fly.

Methods and ways of determining NO_x emission

The maximum emission of nitric oxides was estimated in accordance to the methodology proposed in (Collection of methods for calculating emissions of pollutants into the atmosphere by various industries 1986). The amount of NO_x emitted to the atmosphere (g/s) converted to NO_2, can be counted by using dependence (1) (Krawczyk 2016, Szkarowski et al. 2016, Kuropka 2010, Kormilitsyn and Ezhov 2013, Lee et al. 2006).

Table 1. Values of fan parameters installed in S.A. Russkie Samocvety boiler plant in Sankt Petersburg

Parameter	VD-10	D-10
Output V (m^3/h)	24000	50
Pressure H (kPa)	13	75
Motor power N (kW)	20	30
RPM n (min^{-1})	730	600

Table 2. Values of fan parameters installed in Fourth Krasnovadyeska boiler plant in Sankt Petersburg

Parameter	WC-14-46-8
Output V (m^3/h)	45 810
Pressure H (kPa)	26.93
Motor power N (kW)	55
RPM n (min^{-1})	1000

Table 3. Values of fan parameters installed in Kronshtadtskaja branch of GUP in Sankt Petersburg

Parameter	VD-10	D-13-50
Output V (m^3/h)	25000	51000
Pressure H (kPa)	1.05	1.35
Motor power N (kW)	55	75
RPM n (min^{-1})	950	900

$$P_{NO_2} = 0.001 \cdot B \cdot Q_d \cdot K_{NO_2} \cdot (1 - \beta) \tag{1}$$

where:

B – fuel consumption (high-methane natural gas) (l/s) (with a nominal load it is: 417 l/s for DKVR-20-13 boiler, 530 l/s for DE-25-14 boilers and 1262 l/s for PTVM-50 boilers)

Q_d – fuel calorific value (33.5 MJ/m^3 for DKVR-20-13 boilers, 35.6 MJ/m^3 for DE-25-14 boilers, 33.92 MJ/m^3 for PTVM boiler);

K_{NO_2} – NO_x generation intensity coefficient with the relation to 1 GJ of heat (kg/GJ), in accordance to (Collection of methods for calculating emissions of pollutants into the atmosphere by various industries 1986), for boilers DKVR-20-13, DE-25-14 and PTVM 50 equals 0.11 kg/GJ;

β – coefficient taking into account the influence of technical means lowering NO_x emission (during operation state $\beta = 0$).

The maximum emission of nitric oxides converted to NO_2 was:

– for DKVR 20-13 boiler

$$P_{NO_2} = 0.001 \cdot 417 \cdot 33.5 \cdot 0.11 \cdot 1 = 1.633 \text{ g/s.}$$

– for DE 25-14 boiler

$$P_{NO_2} = 0.001 \cdot 530 \cdot 35.6 \cdot 0.11 \cdot 1 = 2.075 \text{ g/s.}$$

– for PTVM-50 boiler

$$P_{NO_2} = 0.001 \cdot 1262 \cdot 33.92 \cdot 0.11 \cdot 1 = 4.709 \text{ g/s.}$$

The values above the level can be considered as the preliminary emission valuation. The real maximum emission was considered as the most credible reference level in relation to which ecological means are determined.

During the research two methods of reduction of the nitric oxides emission were adopted, namely: fumes recirculation and moisture injection into the combustion area (Juściński 2018, Szkarowski 2002, Szkarowski 2003).

The first method is adopted as technological means aimed at fluid regulation of steam heating temperature, lowering heat intensity of shielding pipes located near burners' flames and decreasing emission of nitric oxides (Szkarowski and Janta-Lipińska 2011, Szkarowski and Janta-Lipińska 2013, Szakrowski and Janta-Lipińska 2009).

However, results of many studies present an inevitable increase of fuel consumption accompanying the use of recirculation in this kind of boilers. Only lowering fees for exceeding maximum allowed emission (MDE) make use of recirculation reasonable from the economical point of view. Due to the lower NO_x emission this method is characterized by 60% effectivity while burning gas, and 40÷50% while burning mazut (Janta-Lipińska and Szkarowski 2018, Szkarowski et al. 2018). This effect is caused by the lower maximum burning temperature and the changed concentration of regulatory substances during dilution by exhaust gases.

Recirculation gases can be brought to blast air, flame root (with appropriate modification of burners) or directly to furnace through slots.

The first of those methods provides the biggest effect. It can be assumed that the bigger the effect the lower the NO_x emission. Additionally, recirculation increases the emission of CO_2, soot and carcinogenic substances (Zhang et al. 2015, Xu et al. 1999, Zandeckis et al. 2010). According to (Collection of methods for calculating emissions of pollutants into the atmosphere by various industries 1986, Pavlenko et al. 2014, Szkarowski 2001), the introduction of recirculating gases into the furnace chamber (with rare exceptions) leads to lowering the boiler efficiency by 0.02÷0.03%, for each 1% recirculation of exhaust gases.

Unfortunately, the analysis of the literature in the area of burning products recirculation does not fully show the influence of the recirculation level on energo-ecological operation indicators in low and medium power industrial-heating boilers.

In majority of studies the methods of lowering the nitric oxides emission are the most important subjects (Janta-Lipińska and Szkarowski 2018, Szkarowski and Janta-Lipińska 2009, Szkarowski et al. 2018, Dal Secco et al. 2015). Lower effectiveness is considered as a side effect of ecological method. This solution was not a subject of subsequent studies.

Due to this fact, this study assumed the steam injection into combustion area as an effective method. The optimal amount of steam injected into the combustion area was around 1% of weight of stream led to air burning (Janta-Lipińska and Szkarowski 2018, Szkarowski 2001, Szkarowski 2002, Szkarowski 2003). The air volume stream for DKVR 20-13 boiler in a nominal mode was 4.61 m^3/s, which is an equivalent of 5.68 kg/s weight stream (at 20ºC). The steam weight stream was equal to 0.057 kg/s or 205 kg/h. For DE 25-14 boiler the air volume stream in a nominal mode was equal to 5.75 m^3/s, which is an equivalent of 6.90 kg/s (at 20ºC). This is an equivalent of 0.069 kg/s steam weight stream or 248 kg/h.

In each case the value of the water-fuel ratio (*WPS*) can be described by the dependence showed below.

$$WPS = \frac{M_p}{M_g} = 0.18 \tag{2}$$

where:

M_p – injected steam weight stream;

M_g – fuel (gas) weight stream.

The potential lower boiler effectiveness will not exceed 1%, which can be wholly compensated by the optimization of a boiler operation mode (by lowering the air excess accompanying the steam injection). The considerations led to a few conclusions. The recirculation method (when compared to the steam injection) is characterized by high demand for material and problems connected with the installation of additional cords in a boiler plant. Recirculation does not lower the total exhaust toxicity indicator (due to chemical unburning). Steam injection into the combustion area was chosen, basing on the drawn conclusions.

Experimental results and discussion

In order to reduce NO_x emissions, water steam was delivered into the combustion zone with the use of injectors of a specific design. In the proposed solution, the standard atomizer had been replaced by a special head design with separate channels for mazut and steam. These injectors of a specific design were placed successively in the GMGB-5.6, DKZ and GMP-16 burners.

In the case of a PTVM-50 boiler equipped with a DKZ burner, the spray head had 12 holes with a diameter of 3 mm, spaced evenly every 30°. In turn, for the DE 25-14 boiler equipped with GMP-16 burner, the spray head had 8 holes arranged alternately (4 with a diameter of 6 mm and 4 with a diameter of 4 mm). The angle of the holes arrangement was 45°. The water steam supplied to the designated flame zones was distributed with the use of an injector.

In the third of the DKVR 20-13 boilers with the GMGB-5.6 burner, water steam was supplied to the flame zones with the use of an injector of a standard head design. The steam was fed simultaneously through the steam and mazut channel, which were a part of the injector. The uniqueness of the proposed solution lies in the way the two channels are connected using a short connector. As a result, the tip of the mazut channel is closed at the end with a plug.

An example of the atomizer solution with the individually selected head for the PTVM-50 boiler equipped with a DKZ burner has been presented in Fig. 1.

The following parameters were changed in order to achieve the complex result with the minimal consumption of steam and the lowest possible influence on the boiler efficiency:

– type and dimensions of pulverizing heads,
– shape of the steam cloud,
– place in which steam is brought into combustion area,
– amount (pressure) of steam and ratio of its streams brought by different head elements to different flame areas (except for DKZ burner).

The realization of the above mentioned research led to establishing optimal, constructive and regime parameters of NO_x emission decrease system (Szkarowski et al. 2016, Janta--Lipińska and Szkarowski 2018, Szkarowski et al. 2018).

Analysis of the received results concerned three levels of potential influence of emission with boilers exhausts on the atmospheric pollution, namely:

1. Maximum computational emission level
2. Maximum actual level defined experimentally during cataloguing of boilers, with real maximum work modes of their operation.
3. Lowered in accordance to preliminary assumptions with 30% emission level

The achieved results are presented in Table 4 and Fig. 5.

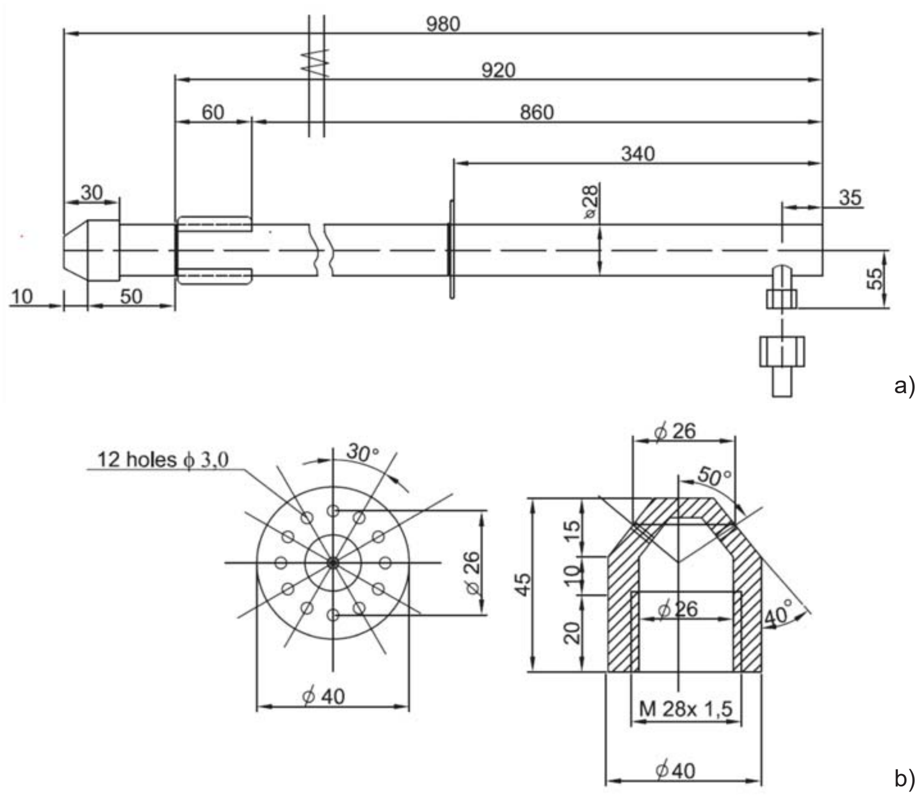

Fig. 1. The technical drawing of the injector a) with the head b) for the PTVM-50 boiler

Table 4. Levels of potential influence of NO_x emissions with boilers exhausts on the atmosphere pollution

Value	Boiler type		
	DKVR 20-13	PTVM-50	DE 25-14
Maximum computational emission level (g/s)	1.633	4.709	2.075
Maximum actual emission level (g/s)	1.419	4.071	1.541
Emission level lowered by 30% (g/s)	0.993	2.85	1.079

The effect of operation of NO_x emission decrease system on each boiler has been presented in the pictures below (Fig. 2–4).

As can be noticed, NO_x emission in the operation state of the boiler can head for computational value only when the nominal boiler efficiency is exceeded (curve 1).

Curve 2 characterizes the optimal operation mode, with NO_x emission decrease system turned on and determined during research and adjustment of the boiler. This mode allows to decrease nitric oxides emission for all boilers by at least 30% of the actual maximum level with the steam

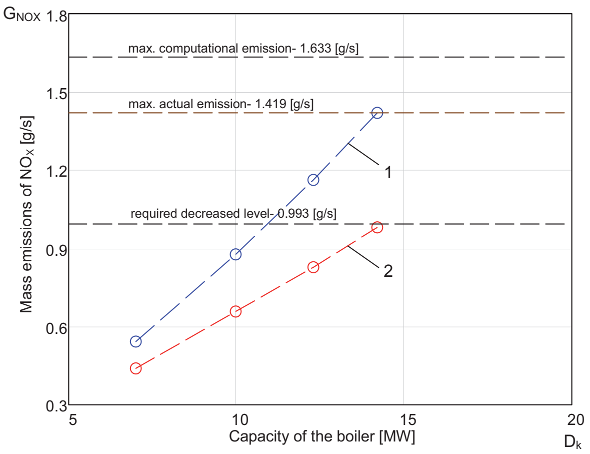

Fig. 2. Weight quantity of nitric oxides emission in DKVR 20-13 efficiency function (1 – boiler during actual operation state, 2 – boiler with turned on NO_x emission decrease system)

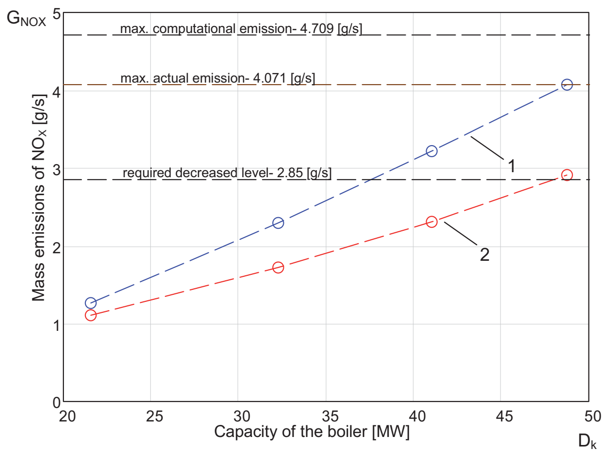

Fig. 3. Weight quantity of nitric oxides emission in PTVM-50 efficiency function (1 – boiler during actual operation state, 2 – boiler with turned on NO_x emission decrease system)

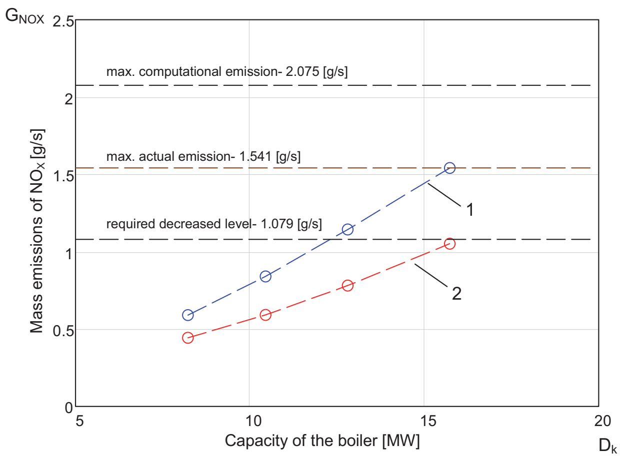

Fig. 4. Weight quantity of nitric oxides emission in DE-25-14 efficiency function (1 – boiler during actual operation state, 2 – boiler with turned on NO_x emission decrease system)

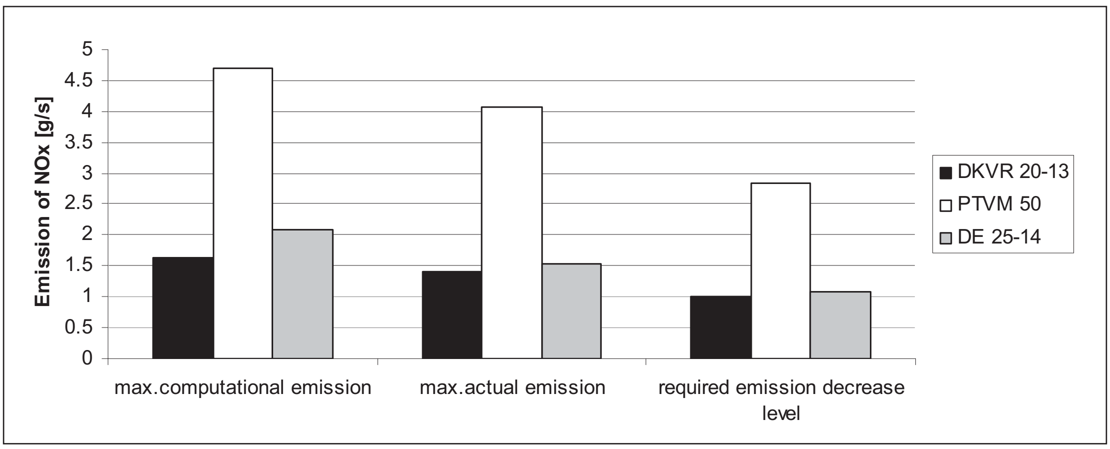

Fig. 5. Comparison of NO_x emission values for DKVR 20-13, PTVM-50 and DE 25-14 boilers

consumption lower than 0.8% boiler efficiency (in the case of PTVM-50 – equivalent steam efficiency). This level of the steam consumption is two times lower than values found in the literature (Janta-Lipińska and Szkarowski 2018, Szkarowski and Janta-Lipińska 2009, Szkarowski et al. 2018).

Steam consumption does not lead to the lower efficiency of the fuel consumption (Janta-Lipińska and Szkarowski 2018, Szkarowski et al. 2018). Injection with the high steam velocity to precisely determined areas of flame's core greatly intensifies mixing of gas streams and air, as well as burning processes. It allows for decreasing excess of air and exhaust heat losses, resulting in the higher boiler efficiency.

Parameters' values characterizing the operation of the constructed system and obtained results from the conducted research were gathered and presented in the tables below (Table 5–7).

Conclusions

The result of the conducted research is a proposition of the effective method leading to the lower emission of nitric oxides for DKVR, PTVM and DE boilers working in the industrial-heating mode. The proposed method is based on injecting steam into the combustion area. Created system reducing nitric oxides emission has a specific construction of injectors, type of pulverizing heads and the place of leading steam to the flame. This study has determined the optimal operation mode of the system, which leads to the lower nitric oxides emission and allows for achieving required 30% emission decrease with a limited consumption of steam for injection (no more than 0.8% of boiler steam efficiency). The proposed steam injection method allows for the increased boiler efficiency, on average, by about 1% ± 0.1. Recommended operation modes of the

Table 5. List of parameters values for DKVR 20-13 boiler (gas fuel)

Parameters	Value of gas pressure before burners (mmH_2O)			
	100	200	300	400
1. Steam efficiency, (t/h)	10.72	15.39	18.97	21.91
2. Gas consumption, (m^3/h)	825	1167	1429	1650
3. Exhaust volume stream (α=1, t=20°C), (m^3/s)	2.58	3.65	4.47	5.16
4. NO_x concentration in exhausts (α=1, t=20°C), (mg/m^3):				
a) actual operation	210	240	260	275
b) with the system turned on	170	180	185	190
5. Nitric oxides mass emission, (g/s):				
a) maximum computational	1.633			
b) maximum actual	1.419			
c) actual operational	0.542	0.876	1.162	1.419
d) with the system turned on	0.439	0.657	0.827	0.980
6. Steam pressure before system injectors, (at)	2.0	3.8	5.5	7.2
7. Steam consumption, (kg/h)	80	110	125	140

Table 6. List of parameters values for PTVM-50 boiler (gas fuel)

Parameters	Number of working burners			
	4	6	8	10
1. Thermal output, (MW)	21.63	32.45	41.23	49.07
2. Gas consumption, (m^3/h)	2495	3777	4795	5744
3. Exhaust volume stream (α=1, t=20°C), (m^3/s)	6.32	9.56	12.14	14.54
4. NO_x concentration in exhausts (α=1, t=20°C), (mg/m^3):				
a) actual operation	200	240	265	280
b) with the system turned on	175	180	190	200
5. Nitric oxides mass emission, (g/s):				
a) maximum computational	4.079			
b) maximum actual	4.071			
c) actual operational	1.264	2.294	3.217	4.071
d) with the system turned on	1.106	1.721	2.307	2.908
6. Steam pressure before system injectors, (at)	1.0	1.0	1.0	1.5
7. Steam consumption, (kg/h)	275	410	550	670

Table 7. List of parameters values for DE 25-14 boiler (gas fuel)

Parameters	Value of gas pressure before burners (mmH_2O)			
	500	800	1200	1800
1. Steam efficiency, (t/h)	12.71	16.17	19.82	24.37
2. Gas consumption, (m^3/h)	970	1230	1505	1845
3. Exhaust volume stream (α=1, t=20°C), (m^3/s)	2.46	3.11	3.81	4.67
4. NO_x concentration in exhausts (α=1, t=20°C), (mg/m^3):				
a) actual operation	240	270	300	330
b) with the system turned on	180	190	205	225
5. Nitric oxides mass emission, (g/s):				
a) maximum computational	2.075			
b) maximum actual	1.514			
c) actual operational	0.590	0.840	1.143	1.514
d) with the system turned on	0.443	0.591	0.781	1.051
6. Steam pressure before system injectors, (at)	0.6	1.1	1.8	2.7
7. Steam consumption, (kg/h)	94	120	157	200

boilers, with a turned on NO_x emission decrease system, do not lead to the lowered net efficiency of the boiler unit.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Acknowledgments

We thank the management and employees of the Boiler Plant S.A. Russkie Samocvety, Fourth Krasnovadyeska Boiler Plant and Kronshtadtskaja branch of GUP (National Unitary Company) "TEK SPB" (Fuel-Energetic Complex Sankt Petersburg) in Sankt-Petersburg for the possibility of performing experimental investigations.

References

Collection of methods for calculating emissions of pollutants into the atmosphere by various industries, L. Gidrometeoizdat, Goskomgidromet,1986. (in Russian)

Dal Secco, S., Juan, O., Louis-Louisy, M., Lucas, J.Y., Plion, P. & Porcheron, L. (2015). Using a genetic algorithm and CFD to identify low NO_x configurations in an industrial boiler, *Fuel*, 158, pp. 672–683, DOI: 10.1016/j.fuel.2015.06.021.

Dubois, V. & Boutin, C. (2018). Comparison of the design criteria of 141 onsite wastewater treatment systems available on the French market, *Journal of Environmental Management*, 216, pp. 299–304, DOI: 10.1016/j.jenvman.2017.07.063.

Janta-Lipińska, S. & Shkarovskiy, A. (2018). The study on decreasing of nitrogen oxides emission carried out on DKVR 10-13 industrial heating boilers, *E3S Web of Conferences,* 44, DOI: 10.1051/e3sconf/20184400056.

Jurik, L., Kaletova, T., Sedmakova, M., Balazova, P. & Cervenanska, A. (2017). Comparison of service characteristics of two town's WWTP, *Journal of Ecological Engineering*, 18, 3, pp. 61–67, DOI: 10.12911/22998993/69365.

Juściński, S. (2018). An analysis of the market of sourcing used oils from tractors in the aspect of the natural environment protection, *Przemysł Chemiczny,* 97, 1, pp. 77–82, DOI: 10.15199/62.2018.1.10. (in Polish)

Kormilitsyn, V. I. & Ezhov, V.S. (2013). Studying the Removal of Nitrogen Oxides from Boiler Flue Gases in Firing Natural Gas, *Thermal Engineering,* 60, 2, pp. 147–152.

Konieczyński, J., Komosiński, B., Cieślik, E., Konieczny, T., Mathews, B., Rachwał, T. & Rzońca, G. (2017). Research into Properties of Dust from Domestic Central Heating Boiler Fired with Coal and Solid Biofuels, *Archives of Environmental Protection,* 43, 2, pp. 20–27, DOI: 10.1515/aep-2017-0019.

Krawczyk, P. (2016). Experimental investigation of N_2O formation in selective non-catalytic NO_x reduction processes performed in stoker boiler, *Polish Journal of Chemical Technology*, 18, 4, pp. 104–109, DOI: 10.1515/pjct-2016-0078.

Kuropka, J. (2010). Reduction of Nitrogen Oxides from Boiler Flue Gases, *Environment Protection Engineering*, 36, 2, pp. 111–122.

Lee, C., Jou, C.G., Tai, H., Wang, C., Hsieh, S. & Wang, H.P. (2006). Reduction of Nitrogen Oxide Emission of a Medium-Pressure Boiler by Fuel Control, *Aerosol and Air Quality Research*, 6, 2, pp. 123–133, DOI: 10.4209/aaqr.2006.06.0002.

Man, C.K., Gibbins, J.R., Witkamp, J.G. & Zhang, J. (2005). Coal characterization for NO_x prediction in air-staged combustion of pulverised coals, *Fuel*, 84, 17, pp. 2190–2195, DOI: 10.1016/j.fuel.2005.06.011.

Park, H.Y., Baek, S.H., Kim, Y.J., Kim, T.H., Kang, D.S. & Kim, D.W. (2013). Numerical and experimental investigations on the gas temperature deviation in a large scale, advanced low NO_x, tangentially fired pulverized coal boiler, *Fuel,* 104, pp. 641–646, DOI: 10.1016/j.fuel.2012.06.091.

Pavlenko, A., Szkarowski, A. & Janta-Lipińska, S. (2014). Research on Burning of Water Black Oil Emulsions, *Rocznik Ochrona Środowiska*, 16, pp. 376–385. (in Polish)

Strelets, K. & Vatin, N. 2015. Dust Features Used to Calculate Dust Removal Performance in Cyclones, *Rocznik Ochrona Środowiska*, 17, pp. 104–112.

Szkarowski, A. (2001). Technology of NO_x Emission Reduction Using Method of Flame Dosed Directional Ballasting, *Rocznik Ochrona Środowiska*, 3, pp. 53–73. (in Polish)

Szkarowski, A. (2002). Principles of Calculation at Suppression of NO_x Formation by a Method of the Dosed Directed Injection of a Water Ballast, *Rocznik Ochrona Środowiska*, 4, pp. 365–378. (in Polish)

Szkarowski, A. (2003). Detailed Problems of the Effective and Ecologically Clean Combustion of Fuel in the Pre-grates of the Furnaces, *Rocznik Ochrona Środowiska*, 5, pp. 67–78. (in Polish)

Szkarowski, A. & Janta-Lipińska, S. (2009). Automatic Control of Burning Quality of Solid Fuel in Industrial Heating Boilers, *Rocznik Ochrona Środowiska*, 11, pp. 241–255. (in Polish)

Szkarowski, A. & Janta-Lipińska, S. (2011). Modeling of Optimum Burning of Fuel in Industrial Heating Boilers, *Rocznik Ochrona Środowiska*, 13, pp. 511–524. (in Polish)

Szkarowski, A. & Janta-Lipińska, S. (2013). Examination of Boiler Operation Energy-ecological Indicators During Fuel Burning with Controlled Residual Chemical Underburn, *Rocznik Ochrona Środowiska*, 15, pp. 981–995. (in Polish)

Szkarowski, A. & Janta-Lipińska, S. (2015). Experimental Research vs. Accuracy of the Elaborated Model, *Rocznik Ochrona Środowiska*, 17, pp. 576–584. (in Polish)

Szkarowski, A., Janta-Lipińska, S. & Gawin, R. (2016). Reducing Emissions of Nitrogen Oxides from DKVR Boilers, *Rocznik Ochrona Środowiska*, 18, pp. 565–578. (in Polish)

Szkarowski, A., Janta-Lipińska, S. & Dąbrowski, T. (2018). Research on Co-combustion of Gas and Oil Fuels, *Rocznik Ochrona Środowiska*, 20, pp. 1515–1529. (in Polish)

Szyszlak-Bargłowicz, J., Zając, G. & Słowik, T. (2015). Hydrocarbon Emissions during Biomass Combustion, *Polish Journal of Environmental Studies*, 24, 3, pp. 1349–1354, DOI: 10.15244/pjoes/37550.

Szyszlak-Bargłowicz, J., Zając, G. & Słowik, T. (2017). Research on Emissions from Combustion of Pellets in Agro Biomass Low Power Boiler, *Rocznik Ochrona Środowiska,* 19, pp. 715–730. (in Polish)

Walery, M. (2014). Medical Waste Management Planning System in the Context of the Model Studies Duration, *Rocznik Ochrona Środowiska,* 16, pp. 260–278. (in Polish)

Xu, H., Smoot, L.D. & Hill, S.C. (1999). Computational model for NO_x reduction by advanced reburning, *Energy & Fuels*, 13, 2, pp. 411–420, DOI: 10.1021/ef980090h.

Xue, S., Hui, S.E., Liu, T.S., Zhou, Q.L., Xu, T.M. & Hu, H.L. (2009). Experimental investigation on NO_x emission and carbon burnout from a radially biased pulverized coal whirl burner, *Fuel Processing Technology*, 90, 9, pp. 1142–1147, DOI: 10.1016/j.fuproc.2009.05.011.

Zając, G., Szyszlak-Bargłowicz, J., Słowik, T., Wasilewski, J. & Kuranc, A. (2017). Emission Characteristics of Biomass Combustion in a Domestic Heating Boiler Fed with Wood and Virginia Mallow Pellets, *Fresenius Environmental Bulletin*, 26, 7, pp. 4663–4670.

Zandeckis, A., Blumberga, D., Rochas, C., Veidenbergs, I. & Silins, K. (2010). Methods of Nitrogen Oxide Reduction in Pellet Boilers, Scientific Journal of RTU, *Environmental and Climate Technologies,* 4, pp. 123–129.

Zhang, X., Zhou, J., Sun, S., Sun, R. & Qin, M. (2015). Numerical investigation of low NO_x combustion strategies in tangentially--fired coal boilers, *Fuel,* 142, pp. 215–221, DOI: 10.1016/j.fuel.2014.11.026.