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EFFECT OF COMBUSTION CHAMBER DIAMETER ON NOX EMISSIONS IN A LIQUID FUEL COMBUSTION STEAM BOILER

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ABSTRACT

Introduction: *Industrial boilers are significant stationary sources of nitrogen oxides (NOx). Reducing the volumetric load rate of the combustion chamber through geometric changes can reduce the maximum flame temperature and NOx formation, but limited field data exists under fixed operating conditions*

Methods: *An A/B comparison was performed on a 495 kW combustion chamber boiler configured with two combustion chamber diameters, keeping the rated output and heating surface constant: Ø 550 mm (boiler I) and Ø 650 mm (boiler II). At half load (Q = 272 kW) and full load (Q = 495 kW), the NOx concentration (mg/m³), thermal efficiency (η), and combustion chamber outlet temperature (°C) were measured. The volumetric load rate of the combustion chamber Qvf (kW/m³) was calculated for each configuration. The mass emission rates were estimated based on a measured flue gas flow rate of ≈770 m³/h per boiler.*

Results: *Increasing the combustion chamber diameter from 550 mm to 650 mm reduced Qvf by 29% (1358 → 963 kW/m³) and lowered the NOx concentration at both loads: from 111 → 101 mg/m³ (half load) and 124 → 113 mg/m³ (full load).At full load, the outlet temperature dropped from 920 °C (Ø550) to 903 °C (Ø650). Thermal efficiency remained almost unchanged (92.3% compared to 92.1% at full load; 93.2% compared to 92.8% at half load; ≤0.4 percentage points difference). The reduction of 11 mg/m³ at full load corresponds to an emission reduction of ≈8.5 g NOx/h (≈85 g over 10 h).*

Discussion: *Reducing the volumetric load rate of the combustion chamber by slightly increasing the combustion chamber diameter leads to a consistent reduction in NOx without any loss of performance or significant loss of efficiency under real operating conditions. Optimizing the combustion chamber geometry is a practical, cost-effective way to control NOx in industrial liquid fuel boilers.*

Keywords: NOx; Industrial boilers; Combustion chamber geometry; Volumetric combustion chamber load; Combustion temperature; Emission control

INTRODUCTION

Nitrogen oxides, commonly referred to as NOx, have become the focus of scientific research and regulatory authorities in recent years, as they have been identified as one of the main causes of numerous harmful phenomena. Their harmful effects are linked to:

-effects on human health,
-reduced visibility and the formation of photochemical smog as a result of reactions between NOx and organic substances under the influence of sunlight,
-the depletion of ozone in the upper layers of the atmosphere,
-the formation of harmful ozone in the lower layers of the atmosphere,
-the formation of acid rain.
From an environmental and health protection perspective, the most important nitrogen oxides are:

-NO – nitrogen monoxide,
-NO_2 – nitrogen dioxide,
-N_2O – nitrous oxide.

More than 90% of the nitrogen oxides released during combustion processes are in the form of nitrogen monoxide (NO), with the remainder being nitrogen dioxide (NO_2). Since nitrogen monoxide is easily converted to nitrogen dioxide in the atmosphere, most environmental regulations treat all nitrogen oxides collectively as NO_2.
Data on the sources of nitrogen oxide emissions show that about two-thirds of total NOx emissions come from combustion processes (Figure 1.1).

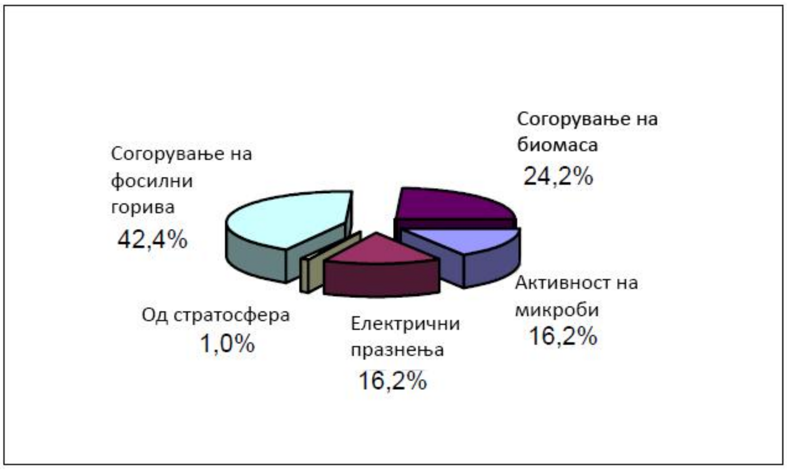

Figure 1.1. Structure of NOx emission sources

These facts have prompted combustion research to develop environmentally friendly solutions, with an increasing focus on striking a balance between the efficiency of combustion plants and minimal environmental impact.

1. MECHANISMS OF NITROGEN OXIDE FORMATION

1.1 Thermal NO (Zeldovich mechanism)

The role of nitrogen from the combustion air in the formation of nitrogen monoxide was explained by Zeldovich. Under stoichiometric conditions, thermal NO is produced by the following reactions:

$$O + N_2 \overset{k_1}{\rightarrow} NO + N \quad (1)$$

$$N + O_2 \overset{k_2}{\rightarrow} NO + O \quad (2)$$

Reaction (1) represents the first step in the formation of nitrogen oxide. A large amount of energy is required to activate it, which according to Zeldovich is E = 314 kJ/mol, as a lot of energy is needed to break the strong bond in the nitrogen molecule N_2. The high temperature required to achieve this activation energy causes the formation of thermal NO to increase exponentially with temperature. Therefore, reaction (1) is the rate-determining step in the formation of thermal NO. Since reaction (1) only proceeds at a significant rate at high temperatures, this formation mechanism is referred to as thermal.

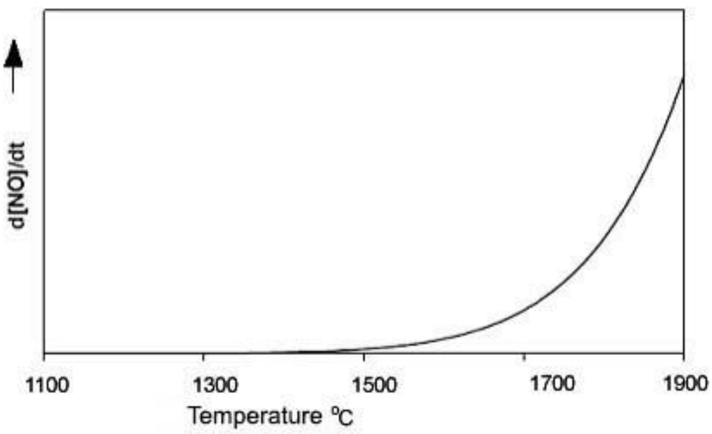

Figure 1.1 Dependence between temperature and the rate of formation of nitrogen oxides

1.2 Prompt mechanism

It has been shown that during the combustion of hydrocarbons, the rate of NOx formation can exceed the rate that would be expected from the direct oxidation of molecular nitrogen (thermal NOx). This discrepancy is particularly pronounced when analyzing the combustion of hydrocarbons under fuel-rich conditions.

This phenomenon can be explained by the formation of nitrogen oxides via a mechanism that differs from the purely thermal mechanism. The process by which nitrogen oxides are formed so quickly—i.e., before they can be formed via the thermal mechanism—is referred to as the prompt mechanism.

2. PRINCIPLES OF NOx EMISSION CONTROL

Measures to control nitrogen oxide emissions can be divided into two main groups:

-Primary measures – directly affect the combustion process by inhibiting certain influencing factors in order to reduce NOx emissions;

-Secondary measures – aim to reduce nitrogen oxides that have already been formed.

The amount of NOx produced during combustion depends primarily on the availability of nitrogen and oxygen, the temperature, the degree of mixing, and the residence time available for the reaction. Controlling these parameters forms the basis for emission reduction strategies and burner design.

The three basic principles of primary control measures relate to reducing the influence of the dominant parameters that promote nitrogen oxide formation:

-Reducing the temperature,
-Reducing the volumetric heat load in the furnace,
-Reducing the oxygen concentration.

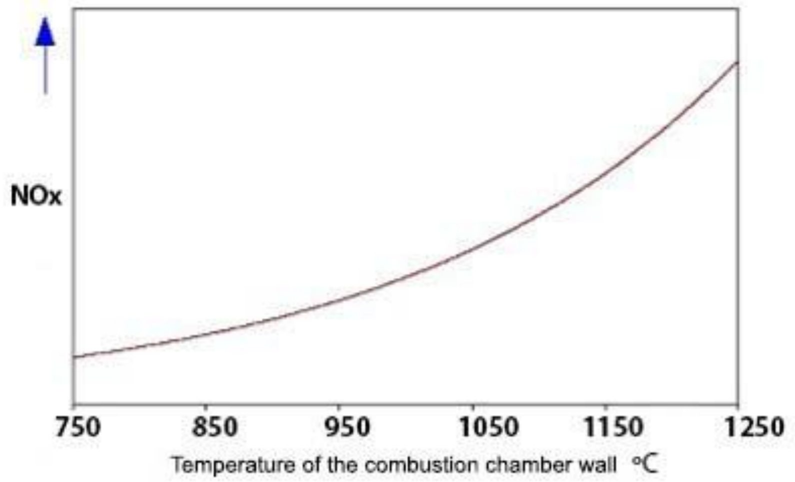

Figure 2. NOx emissions as a function of combustion-chamber wall temperature

3. EXPERIMENTAL RESEARCH AND TESTING

In order to make realistic comparisons of the influence of the design solution on NOx emissions, a study was conducted on two low-pressure steam boilers for heating purposes, each with a maximum output of 500 kW. The two boilers have identical overall dimensions (diameter and length) and a completely identical heating surface. The only difference between them is the diameter of the fire tube: Boiler I has a fire tube diameter of Φ 550 mm, while Boiler II has a fire tube diameter of Φ 650 mm.

The boilers are designed as a block construction (package), are essentially fully automatic, and are fired with heating oil. They are cylindrical, horizontal three-pass boilers: one pass in the fire tube (the combustion chamber) and two passes in the smoke tubes (flue gas pipes).

The boilers operate on the basis of natural water circulation with overpressure on the gas side. The combustion air required for burning the fuel is supplied by a fan that is mounted as part of the burner assembly and blows air into the combustion chamber (flue tube), thereby creating overpressure in the gas duct of the boiler.

In order to enable a comparison between boiler I and boiler II – in particular to determine the nature and extent of the influence of the different design solutions on the flue gas composition and, in particular, on NOx emissions – the composition of the exhaust gases was measured. The measuring points are shown in Figure 3.1. The measurements were first carried out on boiler I with a flame tube diameter of Φ 550 mm and then on boiler II with a flame tube diameter of Φ 650 mm.

In order to obtain reliable and accurate results during boiler operation, the same burner type (Weishaupt WM–L/2-a Monarch) with the same rated output was used for both boilers to avoid errors due to the burner type, combustion control characteristics, and the degree of automation and combustion control. For this reason, the burner was switched from boiler I to boiler II after the measurements on boiler I were completed.

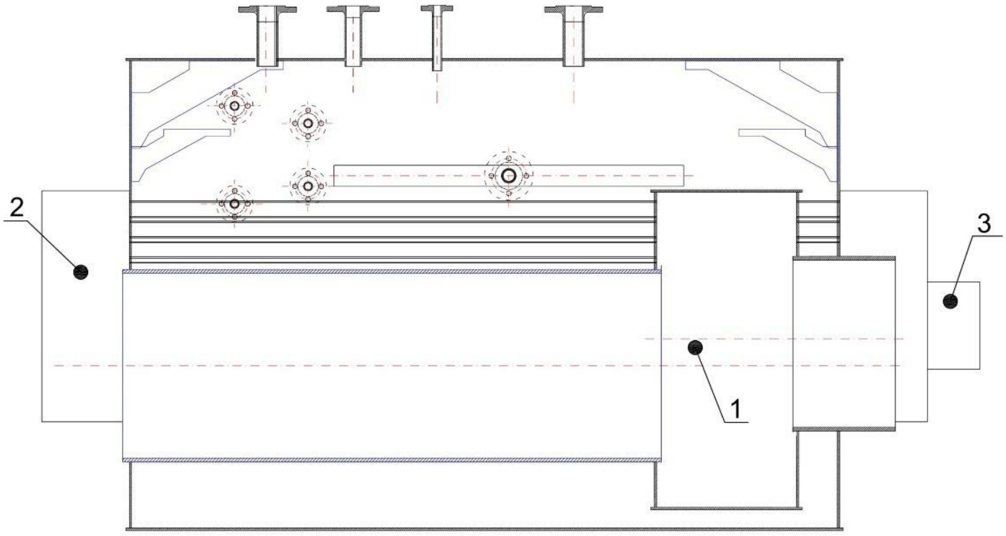

Figure 3.1. Measurement locations (1 – measuring point at the outlet of the first pass; 2 – measuring point at the outlet of the second pass; 3 – measuring point at the outlet of the third pass)

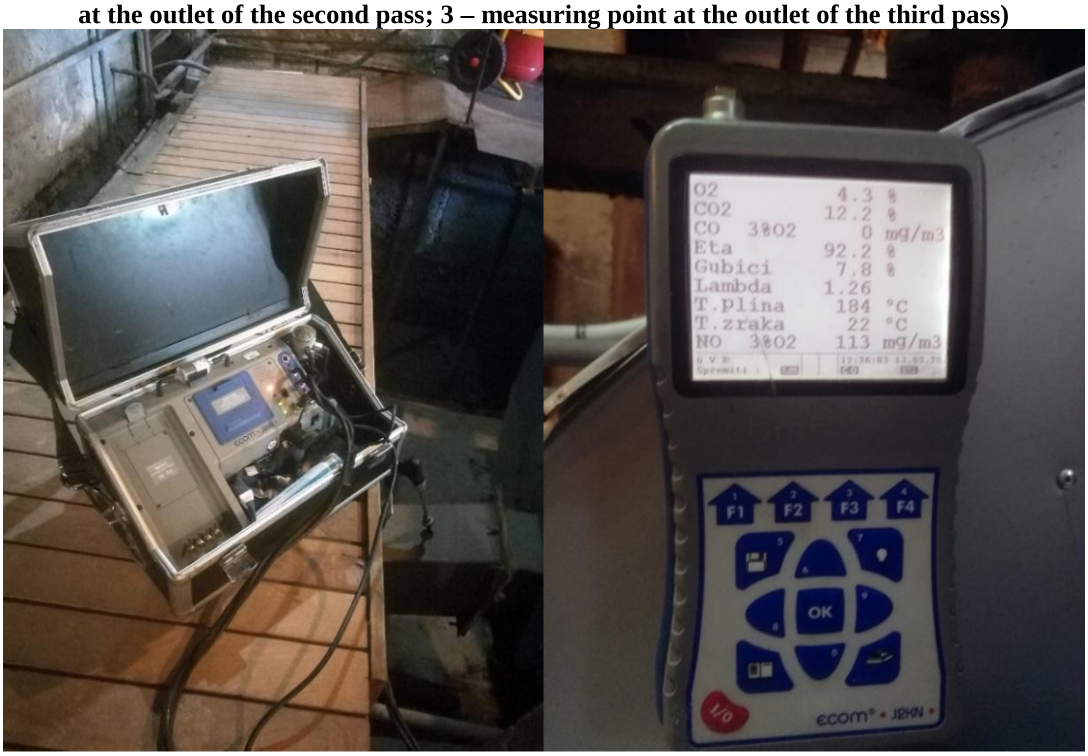

Figure 3.2 and Figure 3.2a. Measurement of the composition of the exhaust gases

4. RESULTS OF THE MEASUREMENTS

After completing the measurements, results were available on the composition of the flue gases in both boilers and on the temperatures at the precisely defined measuring points. The results are shown in Table 4 and in the graphical representation in Figure 4.1.

Table 4. Results of the measurements

	Temperature at the outlet of the combustion chamber[°C]	**Temperature at the outlet of the second pass[°C]**	**Temperature at the outlet of the third pass[°C]**	**Emission of NOx [mg/m3]**	**Thermal efficiency η %**
Boiler I Φ550 during operation at 272 kW	820	278	142	111	93.2
Boiler II Φ650 during operation at 272 kW	805	287	145	101	92.8
Boiler I Φ550 during operation at 495 kW	920	345	183	124	92.3
Boiler II Φ650 during operation at 495 kW	903	353	184	113	92.1

A comparison of the results for the composition of the exhaust gases between boiler I with a flame tube diameter of Φ 550 mm and boiler II with a flame tube diameter of Φ 650 mm reveals clear differences. The tables and graphs show that the NOx emissions in the exhaust gases for boiler I are 111 mg/m³ at a boiler output of 272 kW, while they are 124 mg/m³ at an output of 495 kW. At the same operating loads for boiler II, i.e., at 272 kW, the NOx emissions are 101 mg/m³, while at 495 kW for boiler II they are 113 mg/m³.

5.CONCLUSION

The calculations and measurements carried out for the two boiler variants with different flame tube diameters have yielded several applicable and important findings.

In the first boiler with a flame tube diameter of Φ 550 mm and a burner operating at half power (Q = 272 kW), NOx emissions are 111 mg/m³, while efficiency is η = 93.2%. When the burner is operated at full power (Q = 495 kW) with the same flame tube diameter of Φ 550 mm, the NOx emissions in this case are 124 mg/m³ and the efficiency is η = 92.3%.

In the second boiler with a flame tube diameter of Φ 650 mm and when the burner is operated at half power (Q = 272 kW), NOx emissions are 101 mg/m³, while efficiency is η = 92.8%. When the burner is operated at full power (Q = 495 kW) with the same flame tube diameter of Φ 650 mm, the NOx emissions in this case are 113 mg/m³ and the efficiency is η = 92.1%.

The difference in NOx emissions between the first case, where the diameter of the flame tube is Φ 550 mm, and the second case, where the diameter of the flame tube is Φ 650 mm, is due to the difference in the volumetric heat load of the furnace, i.e., the temperatures in the furnace. Table 4, which lists the measured values, shows that the temperature at the end of the flame tube in boiler I (with a flame tube diameter of Φ 550 mm) is 920 °C, with NOx emissions of 124 mg/m³, and that the theoretically calculated volumetric heat load of the flame tube at a boiler output of 495 kW is Qvf_1 = 1358 kW/m³. In contrast, the temperature at the end of the flame tube in boiler II with a flame tube diameter of Φ 650 mm, measured at the same point as in boiler I, is 903 °C with NOx emissions of 113 mg/m³, and the theoretically calculated volumetric heat load is Qvf_2 = 963 kW/m³.

These measurements show that the difference in NOx emissions between boiler I and boiler II is 11 mg/m³. Considering that, according to theoretical calculations, the volume flow of flue gases in the boilers is approximately 770 m³/h, Boiler II with a flame tube diameter of Φ 650 mm would emit 8470 mg less NOx into the atmosphere per effective operating hour. If we further assume that the boiler operates effectively for 10 hours, the reduction in NOx emissions into the atmosphere would be 84,700 mg/day.

The measurement results show that when comparing the flame tube diameter of boiler I (550 mm) with that of boiler II (650 mm) – an increase in diameter of 17% compared to boiler I, which in this particular case leads to an increase in flame tube volume of approximately 30% – NOx emissions per effective operating hour are reduced by approximately 10%.

These comparisons suggest that increasing the diameter of the flame tube – in this particular case by 100 mm – which, as a design measure, has no impact on the overall design of the boiler and only a minor impact on the production costs of the boiler, leads to a 10% reduction in NOx emissions into the atmosphere. Although 10% may seem small as a percentage, NOx emissions would be reduced by approximately 84,700 g/day or 84.7 kg/day, considering that boilers of this type with a total capacity of approximately 500 MW are installed in Macedonia. This would significantly reduce the impact of NOx on ozone depletion, the greenhouse effect, the formation of acid rain, and negative effects on human health.

REFERENCES

1. Bijedic, M., and S. Delalic. 2003. Thermodynamics and Thermotechnics. Tuzla.
2. Bogner, M. 1987. Thermal Technician – Handbook of Thermotechnics, Thermal Power Engineering, and Process Engineering. Belgrade.
3. Buderus. 2005. Steam Boilers Logano. Buderus.
4. Guric, V., and M. Bogner. 1980. Steam Boilers – Theoretical Fundamentals and Calculation. Belgrade.
5. Jurnal Teknologi (Sciences & Engineering). 2015. Jurnal Teknologi (Sciences & Engineering) 76 (1): 115–123.
6. Kozić, Đ., B. Vasiljević, and V. Bekavac. 2006. Handbook of Thermodynamics in SI Units. Faculty of Mechanical Engineering, Belgrade.
7. Petrovski, I. 2004. Steam Boilers. Faculty of Mechanical Engineering, Skopje.
8. Petrovski, I. n.d. Nitrogen Oxides in the Gases of Steam Generators Fired with Liquid Fuel. Faculty of Mechanical Engineering, Skopje.
9. SAACKE. 1993. Primary Measures for NOx: Technical Information. 2nd ed. Bremen.
10. The Babcock & Wilcox Company. n.d. "Nitrogen Oxides Control." In Technical Documentation of The Babcock & Wilcox Company.
11. U.S. Department of Energy. 2004. Improving Steam System Performance. 2nd ed.
12. Unknown Author. 1973. Article on Nitrogen Oxides. Available at https://www.tandfonline.com/doi/pdf/10.1080/00022470.1973.10469746.