

## The Emission of Carbon Monoxide and Nitrogen Oxides from Boilers Supplied by a Pellet under the Influence of Changes in the Air-Fuel Equivalence Ratio

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### ABSTRACT

The aim of the experimental research was to determine the impact of changes in the air-fuel equivalence ratio during the combustion of wood pellet in the boiler on the CO and NO<sub>x</sub> emissions. In order to realize the tests, 10 kW wood pellet boiler equipped with a dedicated wood pellet burner was employed. On the basis of the research, the relationship between the level of harmful substances emitted under the influence of changes in the air-fuel equivalence ratio was presented. The obtained results and conclusions based on them can be used to optimize the design of heating devices fed by wood pellets.

**Keywords:** heating boiler, wood pellet, air-fuel equivalence ratio, CO, NO<sub>x</sub>

### INTRODUCTION

The studies on the emission of harmful substances from solid fuel boilers have been conducted for several years [Creutzig et al. 2015; Obernberger et al. 2004]. The majority of the works show an identical approach of scientists to the research on boilers, describing the boiler as a technical object interacting between man and the environment [Rashid et al. 2014; Sippula et al. 2008]. Previous studies showed a significant impact of technical parameters of fuels on the variability of mass concentrations of CO and NO<sub>x</sub> emitted from their combustion. Moreover, the studies on co-combustion of carbon fuels with wood and non-wood biomass show convergent courses of emitted harmful substances, which allows the application of analogous research methods [Shao et al. 2012; Sommersacher et al. 2012]. In the publication [Ciupek et al. 2019], with reference to thermodynamics, the solid fuel boiler was considered as a closed heterogeneous system with a strong impact on the external environment, conditioned by the physicochemical parameters of the burnt fuel. The parameters of the burnt

fuel significantly influenced the change of the boiler operation parameters through the changeable physical and chemical properties of the fuel. This approach involved mapping the scale of the problem in terms of the emissions of harmful substances, without reference to the chemical aspects of the combustion process. In the publications [Caseiro et al. 2009; Verma et al. 2011], the subject of harmful substances emission from the boiler equipment not subject to environmental register was discussed. They show that many district heating plants located close to each other have a significant contribution to the emission of harmful substances in a given area. The concentrations of harmful substances in flue gases emitted by boilers calculated by the researchers exceeded the assumptions of standards and directives many times over.

The scale of the problem related to the emission of harmful substances in Poland caused by the use of heating boilers for solid fuels shows the necessity to introduce modern technologies allowing to significantly reduce the amount of harmful substances emitted to the environment.

The issues related to the influence of the chemical composition of combusted fuels on the emission of harmful substances from boilers are discussed in the publications [Joseph et al. 2018; Staiger et al. 2005; Stubenberger et al. 2008]. The publications [Barranco et al. 2007; Carrillo et al. 2014; Runge et al. 2014] show that the level of harmful emissions is directly related to the technical parameters of the appliance and the fuel being combusted.

Wood pellets with technical parameters described as: combustion heat ( $H_s$ ), moisture content ( $W_t$ ), ash content ( $A^a$ ) and volatile components ( $V^{daf}$ ) were selected for the study. The heat and emission work of the boiler during operation at its nominal output for three different excess air coefficients was analysed. The results obtained were presented in summary tables and on the figures presenting mass distributions of CO and  $NO_x$  emitted in relation to the air-fuel equivalence ratio ( $\lambda$ ).

## METHODS

The test facility used in the tests was a pellet boiler with a nominal output of 10 kW equipped with an automatic pellet burner, meeting the technical requirements for boilers built in accordance with EU Directive 2015/1189. The technical parameters of the fuel are shown in Table 1.

During the tests, the thermal power of the boiler oscillated around the rated power of the device. The amplitude of thermal power varied within  $\pm 1$  kW from the rated power. The BCA-01 flue gas analyser was responsible for the measurement of the  $O_2$  content in the exhaust gases. Its measurement range ranged from 0% to +25% of oxygen volume, and the measurement error was  $\pm 0.8\%$ . The TESTO 350 XL exhaust gas analyser was responsible for the measurement of mass concentrations of CO and  $NO_x$ . The analyzer was equipped with photochemical measurement targets. The analysis time was set as one sample per second. The accuracy of CO measurement was  $\pm 5\%$  and for  $NO_x$   $\pm 5\%$ . Thermocouples type

K (NiCr-Ni) with measuring range from  $-200^\circ\text{C}$  to  $+1370^\circ\text{C}$  and measuring error of  $\pm 0.4^\circ\text{C}$  were used for temperature measurement. The heat loss in the heating system amounted to approx.  $-2.5\%$ . The system of plate heat exchangers was responsible for the reception of the generated heat.

The measurements were carried out for three test cycles. The tests were carried out for three different air-fuel equivalence ratios:  $\lambda_1 = 2.30$ ,  $\lambda_2 = 1.90$  and  $\lambda_3 = 1.50$ . In the first cycle, the emission level of substances harmful to the automatically fired boiler was tested at  $\lambda_1 = 2.30$ . In the next cycle, the tests for emission of harmful substances at  $\lambda_2 = 1.90$  were carried out. In the last cycle, the same tests were carried out as for the previous ones, but  $\lambda_3 = 1.50$ .

Registration of the measurement data was based on a test stand equipped with a PC and a system of measurement cards type ADAM-4118. The computer setup was responsible for collecting the measurement data from the exhaust gas analyzers, while the measurement cards and a dedicated registration program were responsible for the temperature measurement. The mass concentrations of CO and  $NO_x$  were converted to  $\text{mg}/\text{m}^3$  for 10%  $O_2$  in the exhaust gas. The conversion resulted from the emission assumptions made for boilers in accordance with the PN-EN 303-5:2012 standard. The results of the flue gas temperature were averaged by the measurement carried out by five thermocouples. In order to determine the fuel consumption of the boiler, a weighing station was used, measuring the mass of fuel charge before and after the tests. On the basis of the fuel consumed during the tests, the mass flow of the fuel burnt was determined. In addition, the air-fuel equivalence ratios ( $\lambda$ ) and boiler heat efficiency ( $\eta$ ) were calculated on the basis of the data recorded.

## RESULTS

The results of tests for the first cycle are presented in Table 2. The obtained emission distributions of harmful substances are presented in Figs. 1 and 2. The boiler operated in the range of air-fuel equivalence ratio from 1.75 to 2.85. The range of flue gas temperature ranged from  $83^\circ\text{C}$  to  $104^\circ\text{C}$ . The efficiency of the combustion process ranged from 93% to 97%.

The results for the second cycle of tests are presented in Table 3. The obtained distributions

**Table 1.** Technical parameters of fuel used in tests

Fuel	Combustion heat, MJ/kg	Moisture, %	Ash, %	Volatile components, %
Wood pellet	18.20	10.10	0.70	67.60

**Table 2.** Results for the first cycle test

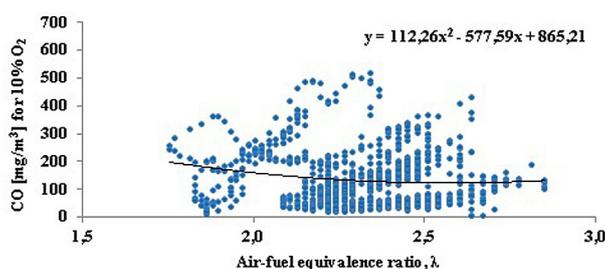
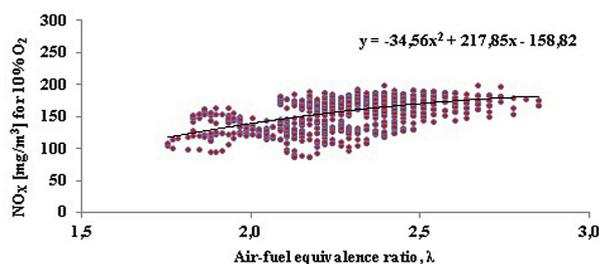
Specification	O <sub>2</sub> , %	CO, mg/m <sup>3</sup>	NO <sub>x</sub> , mg/m <sup>3</sup>	T <sub>SPR</sub> , °C	λ	η, %
average	11.85	133.93	159.22	93.00	2.32	95.18
minimum	9.00	8.00	87.00	83.00	1.75	93.20
maximum	13.60	521.00	199.00	104.00	2.85	96.60

of harmful substances emission are presented in Figs. 3 and 4. On the basis of the results it was observed that the reduction of air-fuel equivalence ratio caused an increase in the amount of CO emitted in relation to the first cycle of tests by 112 mg/m<sup>3</sup>. The NO<sub>x</sub> emissions decreased by about 4 mg/m<sup>3</sup>. The boiler operated in the air-fuel equivalence ratio from 1.58 to 2.37. The flue gas temperature range ranged from 99°C to 138°C. The efficiency of the combustion process ranged from 89% to 94%.

The results for the third test cycle are presented in Table 4. The obtained emission distributions of harmful substances are presented in Fig. 5 and 6. On the basis of the results, it was observed that the reduction of air-fuel equivalence ratio caused an increase in the amount of CO emitted in relation to the first test cycle by 184 mg/m<sup>3</sup> and in relation to the second test cycle by 72 mg/m<sup>3</sup>. The NO<sub>x</sub> emissions from the first test cycle decreased by approximately 8 mg/m<sup>3</sup> and from the second test cycle – by 4 mg/m<sup>3</sup>. The boiler operated in the air-fuel equivalence ratio range from 1.36 to 1.86. The flue gas temperature ranged from 139°C to 150°C. The efficiency of the combustion process ranged from 88% to 91%.

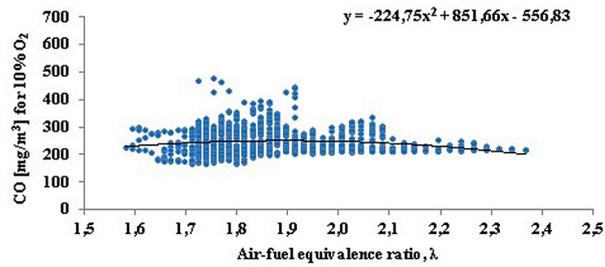
## CONCLUSIONS

The studies on the influence of air-fuel equivalence ratio (λ), change on CO and NO<sub>x</sub> emission from a pellet boiler were carried out. On the basis of the results obtained, it can be seen that the decrease in the amount of air supplied to the combustion process affects the increase in CO emissions. In the case of NO<sub>x</sub>, a reduction in emissions was observed. Decreasing the air-fuel equivalence ratio (λ) caused an increase in the temperature of exhaust gases. From the thermodynamic point of view, the change in the temperature of flue gases caused a decrease in the intensification of heat exchange between flue gases and the heating factor, which resulted in a 5% decrease in the efficiency of the combustion process. The results obtained from the research give grounds for further research on the influence of the air-fuel equivalence ratio (λ), as well as the changes on the chemical composition of exhaust gases. In the case of classic boiler designs, the reduction of the incoming air flow rate has a positive effect on the reduction of NO<sub>x</sub> emissions; however, it results in a multiple increase of CO.

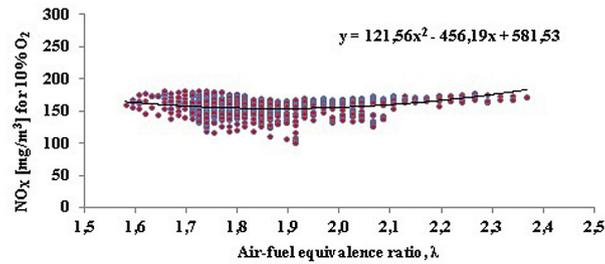
**Fig. 1.** The course of CO emissions for first cycle of research**Fig. 2.** The course of NO<sub>x</sub> emissions for first cycle of research

**Table 3.** Results for the second cycle test

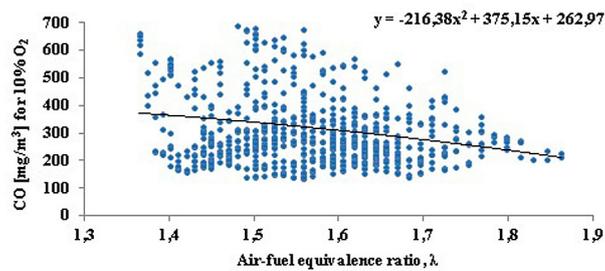
Specification	O <sub>2</sub> , %	CO, mg/m <sup>3</sup>	NO <sub>x</sub> , mg/m <sup>3</sup>	T <sub>Spn</sub> , °C	λ	η, %
average	9.68	245.48	155.89	117.00	1.87	92.40
minimum	7.70	166.00	102.00	99.00	1.58	89.50
maximum	12.10	480.00	182.00	138.00	2.37	94.50



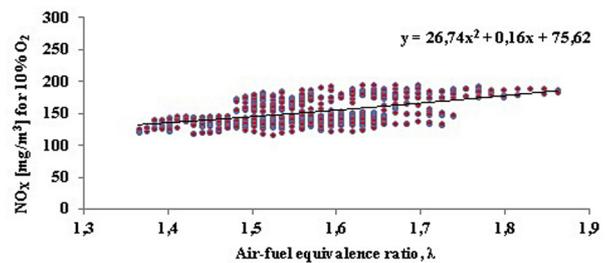
**Fig. 3.** The course of CO emissions for second cycle of research



**Fig. 4.** The course of NO<sub>x</sub> emissions for second cycle of research



**Fig. 5.** The course of CO emissions for third cycle of research



**Fig. 6.** The course of NO<sub>x</sub> emissions for third cycle of research

**Table 4.** Results for the third cycle test

Specification	O <sub>2</sub> , %	CO, mg/m <sup>3</sup>	NO <sub>x</sub> , mg/m <sup>3</sup>	T <sub>SP</sub> , °C	λ	η, %
average	7.53	317.40	151.77	145.00	1.57	89.25
minimum	5.60	134.00	117.00	139.00	1.36	88.00
maximum	9.70	895.00	196.00	150.00	1.86	90.60

## Acknowledgments

The work was carried out within the framework of a scientific project no. POIR.04.01.04-00-0135/16 „Niskoemisyjny kocioł grzewczy na paliwo stałe z możliwością wykorzystania energii odpadowej”, financed by NCBR – Poland.

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