METHODOLOGY OF EXPERIMENTAL OPTIMIZATION OF ATMOSPHERIC BURNERS FOR HOUSEHOLD APPLIANCES

by

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The aim of this experimental research is to confirm the correctness of the proposed methodology for optimizing atmospheric gas burners. Also, the burner was tested in actual conditions. The object of this experimental optimization is a typical modern atmospheric gas burner for households (required heat output for average households ranges from 8-12 kW) to which the proposed methodology will be applied in order to optimize its design characteristics and performance to obtain energy efficient and an environmentally friendly device.

Key words: *experimental optimization, atmospheric burner, energy efficiency, environmentally friendly device*

Introduction

Extensive and very intensive experimental research was conducted, which includes the diameter of the burner fuel nozzle, d_{ml}, the distance of the nozzle outlet from the burner inlet, Δh_{ml}, the area of the flame openings (number of flame openings), NO_x emissions, CO emissions, the diameter of the cylindrical mixer burner (mixer neck), type of gaseous fuel used, change in power range, the primary coefficient of excess air as well as investigation of the burner installed in a selected gas device performance. Modern atmospheric burners, which have been constructed for higher thermal power (of the order of 10 kW) compared to conventional atmospheric burners (of the order of 2 kW), have retained the Venturi system of mixing fuel and air and designed flame ports not to form individual flames, as is often the case with classical systems, but more or less to form one global flame. A higher coefficient of excess air reduces the degree of usefulness of the device [1]. In order to confirm the operating characteristics of the optimized burner in actual conditions, it was necessary to choose a gas device that is used in an average household. The use of gaseous fuel for heating purposes is increasingly suppressing the use of solid and liquid fuels, especially when it comes to individual boiler rooms related to households. It is important to emphasize that as part of encouraging the development of the domestic economy, it was decided that the manufacturer of the gas appliance in question be a representative of the domestic gas appliance industry. The gas heater Alfa 9, manufactured by the domestic Alfa-Plam Vranje company, was chosen as a representative gas device, in which the optimized gas burner will be tested at actual operating conditions.

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Experimental installation

The independent influencing parameters that were optimized are: nozzle diameter, distance of the nozzle from the entrance of the mixer, diameter of the Venturi mixer, area and shape of the flame ports. During the tests, different types of fuel were used: LPG (a commercial mixture of propane and butane), natural gas, and biogas. In order to realize the experimental tests carried out in this work, it was necessary to form an experimental installation. Then a reference or starting point was determined by determining the performance of the Alfa 9 gas heater, in which the newly obtained burner should be installed, equipped with its original burner, with the aim of determining the initial level of performance of the selected gas control device.

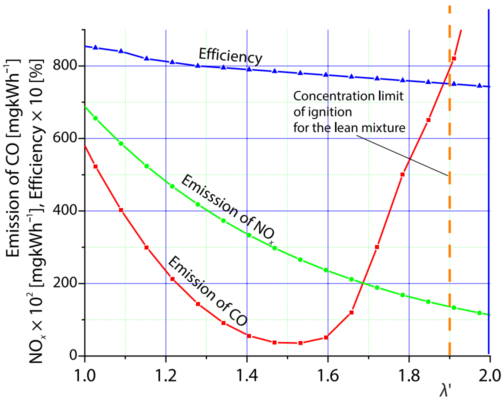

Figure 1. Dependence of CO and NO$_x$ emissions as well as the efficiency from the primary excess air coefficient λ'

Determination of nozzle diameter

Based on the calculation of atmospheric burners, as well as the analysis of the mathematical model of the burner and the available pressure in the installation for different gaseous fuels (LPG, natural gas, biogas), the diameter of the nozzle, d_{ml}, (was calculated for the different types of gaseous fuel that were used during the test: d_{ml} = 2.25 mm for LPG, for natural gas, d_{ml} = 4.5 mm for biogas.

Determination of the distance of the nozzle outlet from the burner mixer inlet

The value of the primary excess air coefficient, λ', affects the emission of combustion products and efficiency, which is shown in fig. 1, which was obtained on the basis of numerical research.

As can be concluded from fig. 1, in order to satisfy the optimization criteria of emissions limits of 50 mg/kWh, the value of the primary excess air coefficient λ' should range from 1.4 to 1.54. This test aimed to determine the influence of the distance from the nozzle outlet to the burner mixer inlet Δh_{ml} on λ'. Namely, the idea was to determine the change in the value of λ' when Δh_{ml} increases from 0 to a specific value, that is, to determine whether λ' increases or decreases. The optimized parameter Δh_{ml} and its influence on the burner's performance, specifically on λ', can only be determined experimentally. The lay-out of the experimental installation used is given in fig. 2. Namely, on this occasion, in order to avoid an explosive mixture of fuel and air, CO_2 was used instead of fuel since it has the same molar mass, the same density as propane C_3H_8, while at the exit from the mixer,

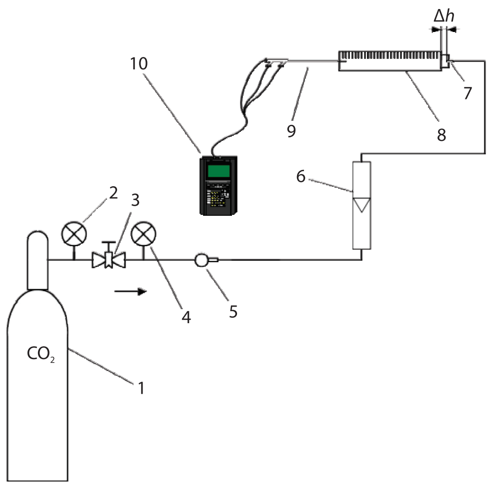

Figure 2. Schematic representation of the experimental installation: *1 – CO_2 gas tank, 2 – manometer, 3 – regulation valve, 4 – manometer, 5 – pressure regulator, 6 – rotameter, 7 – nozzle d_{ml} = 2.5 mm, 8 – burner, 9 – gas analyzer probe, and 10 – gas analyzer Testo 350XL*

the content of CO_2 in the achieved mixture of CO_2 + air have been measured, using a gas analyzer, and based on that, the primary air coefficient was calculated. The flow of CO_2 is determined to model the nominal thermal powers of 100%, 66%, and 33%, concerning the full capacity of the given burner. In each of the mentioned tests, Δh_{ml} was varied.

From the resulting diagram shown in fig. 3 (on which the dependence of the λ' – primary air coefficient on Δh_{ml} is given, it is clearly seen that the primary coefficient of excess air λ' decreases with the increase in the distance from the nozzle exit to the burner mixer inlet Δh_{ml}, which was expected considering the fuel jet expansion angle. It is also noticeable that there is no significant difference in the results when varying the fuel flow, that is, the thermal power of the burner. Also, the diagram in fig. 3 shows that the maximum value for λ' is obtained when positioning the nozzle at the very entrance to the mixer. As the goal is to obtain the value of λ' in the interval 1.4-1.54, which can be seen in fig. 1, it can be concluded that in order to reach the optimal operating conditions, the distance $\Delta h_{ml} = 0$ is chosen.

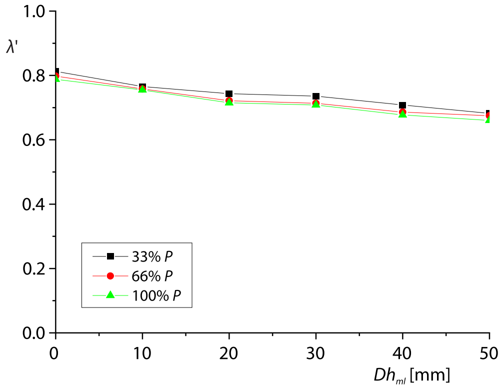

Figure 3. Dependence of λ' – the primary air coefficient on Δh_{ml}; *P* – thermal power

Primary coefficient of excess air as a function of combustion chamber pressure drop

The gas burner-combustion chamber system has certain pressure drop, *i.e.* pressure losses, caused by the geometry of the burner and the combustion chamber. A schematic representation of the experimental installation is shown in fig. 4. The increase of pressure drop directly affects the amount of ejected primary air [2], *i.e.*, the decrease of the primary air coefficient, λ', which is reflected in the combustion process.

The results of the effect of the pressure drop in the combustion chamber on the value of the primary coefficient of excess air are shown in fig. 5.

From the results shown, fig. 5, it can be seen that with a decrease in the underpressure in the combustion chamber (the assumption is that this decrease in pressure causes an increase

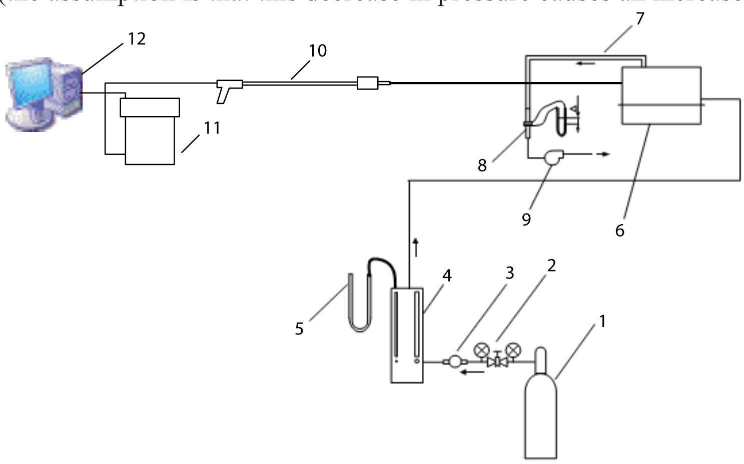

Figure 4. Schematic representation of the experimental installation; *1– CO_2 gas tank, 2 – regulation valve, 3 – pressure regulator, 4 – rotameter, 5 – manometer with U-tube, 6 – combustion chamber with burner, 7 – line for a mixture of CO_2 and air, 8 – measuring aperture, 9 – fan, 10 – gas analyzer probe, 11 – gas analyzer TESTO 360, and 12 – computer*

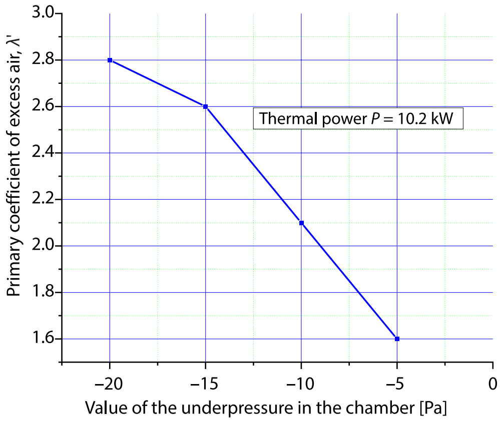

Figure 5. Primary coefficient of excess air λ' as a function of underpressure in the combustion chamber

in resistance in the burner-combustion chamber system) there is a decrease in the value of the primary coefficient of excess air λ'.

Determining the performance of the Alfa 9 gas heater

Since the Alfa 9 gas heater was chosen as the control device for testing the operating characteristics of the optimized burner in actual operating conditions, it was necessary to determine the operating characteristics of this gas device in its original version. The experimental installation shown in fig. 6 gave the possibility of testing the performance of the gas device when using different types of fuel (LPG, natural gas, biogas).

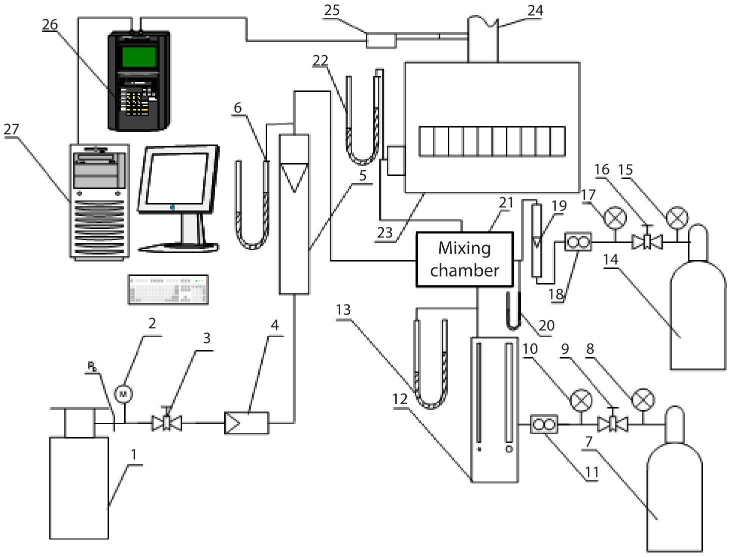

Figure 6. Schematic representation of the experimental installation:
1– gas tank with C_3H_8 + C_4H_{10}, 2 – manometer, 3 – regulation valve, 4 – pressure regulator, 5 – rotameter, 6 – manometer with U-tube, 7 – gas tank with CH_4, 8 – manometer, 9 – regulation valve, 10 – manometer, 11 – pressure regulator, 12 – rotameter, 13 – manometer with U-tube, 14 – gas tank with CO_2, 15 – manometer, 16 – regulation valve, 17 – manometer, 18 – pressure regulator, 19 – rotameter, 20 – manometer with U-tube, 21 – mixing chamber, 22 – manometer with U-tube, 23 – gas heater Alfa 9, 24 – exhaust of combustion products, 25 – gas analyzer probe, 26 – gas analyzer, and 27 – computer

Testing of the reference burner integrated with the Alfa 9 gas heater

The chosen reference burner was integrated with the Alfa 9 gas heater to test the performance of this burner in the gas device for which it is intended and get the reference performance parameters of the heater. The fuel used during the test was LPG, and the burner's heat output varied from 33% (3.4 kW) to 100% (10.2 kW). In addition, the emission of combustion products (CO and NO_x) was measured. During the tests of the reference burner, the obtained results were averaged for different thermal powers and shown in diagrams presented in figs. 7-9, where it could be seen that the emissions of CO, NO_x, and total air coefficient λ_{tot}, increase with the increase of thermal power.

Design improvements of the reference burner

For the initial phase of testing, the reference burner manufactured by BCT was selected as the first phase of the burner, which should meet the required performance specified in the task of this work. It is an injector burner with a classic Venturi mixer, with slit-shaped flame openings [3] arranged in three rows with a nominal power of 10.2 kW. The burner is multi-fuel, intended for operation with liquefied petroleum gas, natural gas, and biogas.

In order to increase the primary air coefficient, the burner flame ports area was increased. It was found that the increase of 1.07 times satisfies the goal of emission limits for the appliance. The dependence of CO and NO_x emissions and the total coefficient of excess air λ_{tot} are shown in diagrams in figs. 7-9.

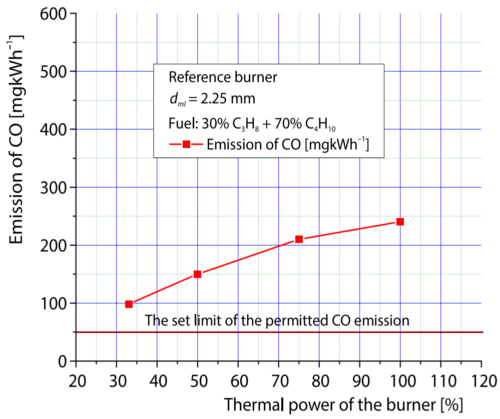

Figure 7. Dependence of CO emission on the thermal power of the burner

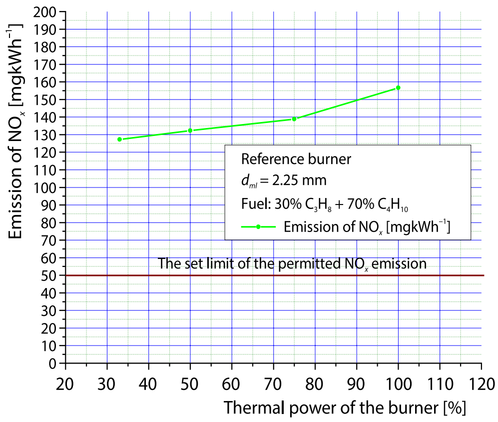

Figure 8. Dependence of NO_x emission on the thermal power of the burner

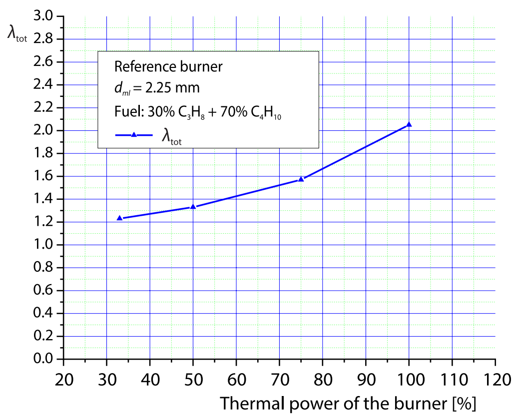

Figure 9. Dependence of λ_{tot} – total coefficient of excess air on the thermal power of the burner

Experimental confirmation of the burner optimization methodology

In order to determine the performance of the tested gas device and burner under the conditions of using fuel of different composition and quality, different thermal powers, and coefficients of excess air, the following parameters were varied: types of fuel (LPG – 30% mol C_3H_8, 70% mol C_4H_{10}, d_{ml} = 2.25 mm; technical methane – 99.5% mol CH_4, 0.5% mol N_2, d_{ml} = 2.5 mm; natural gas – 79.6% mol CH_4, 0.4% mol N_2, 20% mol CO_2, d_{ml} = 2.5 mm; and biogas – 59, 7% mol CH_4, 0.3% mol N_2, 40% mol CO_2, d_{ml} = 4.5 mm), operating range of the gas device or burner (in terms of power), primary coefficient of excess air, pressure drop in the combustion chamber. The main parameters monitored and measured during these tests were: flame shape and stability, CO and NO_x emissions, and coefficient of λ_{tot}.

The influence of different types of gaseous fuels on burner operation

The fuel quality is an essential parameter, especially its influence on the emission during the operation of low emission atmospheric burners [4]. In the experiments conducted during this test, the influence of the type of gaseous fuel on flame stability, the dynamic power range [5] of the optimized burner, and the emission of combustion products (CO and NO_x) were checked. Two series of measurements were carried out, each with a different type of gaseous fuel. Optimized burner 1 and LPG (30% mol C3H8, 70% mol C4H10) were used in the first series of measurements, and the second series of measurements, optimized burner 1 and technical methane (99.5% mol CH_4, 0.5% mol N_2), natural gas (79.6% mol CH_4, 0.4% mol N_2, 20% mol CO_2) and biogas (59 .7% mol CH_4, 0.3% mol N_2, 40% mol CO_2). In both cases, the heat power was varied from 33% (3.4 kW) to 100% (10.2 kW).

Analysis of results

Based on the set goals, during the implementation of the optimization methodology of the subject atmospheric burner, in terms of stability of operation, the dynamic range of operation (1:3), emissions (CO emission < 50 mg/kWh, NO_x emission < 50 mg/kWh), numerous experimental tests, described in previous chapters. For the purposes of the final consideration, which should provide an answer to the tasks set in this work, the test results were taken with the following adopted parameters: nozzle diameter d_{ml} = 2.25 mm, fuel – LPG (propane C_3H_8 30% mol, butane C_4H_{10} 70% mol), secondary air vents fully open, tested burners (selected reference burner, optimized burner 1) were integrated into the Alfa 9 gas heater, the thermal power of the device varied from 33% (P = 3.4 kW) to 100% (P = 10.2 kW) according to the required dynamic operating range of 1:3.

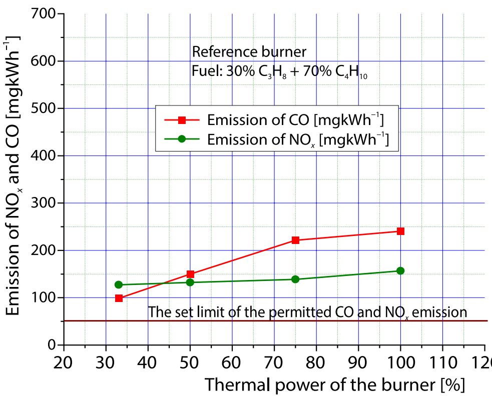

Figure 10. Dependence of NO_x and CO emissions on thermal power of reference burner

Reference burner

The reference burner was integrated into the control gas device Alfa 9 and tested as a starting point for optimization in actual operating conditions. During the test of the reference burner, for previously defined test conditions, NO_x and CO emissions were obtained and averaged for different thermal powers, as shown in fig. 10.

The obtained results of the experimental tests of the reference burner show that the measured NO_x and CO emissions exceed the prescribed limit of 50 mg/kWh over the entire dynamic range of operation (1:3), while the measured total coefficient of excess air, λ_{tot}, ranges from 1.23-2.05. Such test results indicated the need for appropriate reconstructive interventions on the chosen reference burner to satisfy the emission limits.

Optimized Burner 1

In order to improve the results obtained during the test of the reference burner, since the burner did not meet the set requirements, the following reconstruction procedures were performed on the reference burner in accordance with the performed numerical and experimental tests:

– The initial arrangement of flame openings was replaced by a new one – three rows of equal openings of the order of 10 mm × 1 mm in size, with an increase in the distance between the rows of flame openings by 1.2 times.
– The length of the burner has been increased;
– The initial area of the flame holes increased 1.07 times.

It can be seen that with an increase in the A_{PL}/A_{PLO} ratio (A_{PLO} – initial area of the flame openings, A_{PL} – current area of the flame openings), CO and NO_x emissions decrease. Namely, with the increase in the area of the flame ports, the ratio A_{PLO}/A_{PL} increases, increasing the coefficient of excess air λ'.

The test of the optimized burner 1 was performed under the same conditions under which the test of the reference burner was performed. The obtained NO_x and CO emission results during the test of the optimized burner 1, are also averaged for different thermal powers and shown in fig. 11.

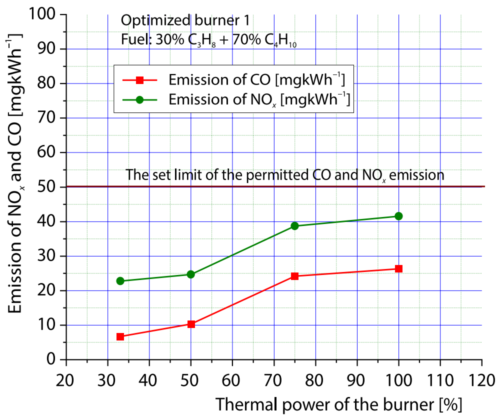

Figure 11. Dependence of NO_x and CO emissions on thermal power of optimized Burner 1

During the testing of the optimized Burner 1, the results obtained show that the measured emissions of NO_x and CO are below the set limit emission of 50 mg/kWh over the entire dynamic range of operation (1:3), which means that the requirements regarding the permitted emission of pollutants in combustion products are and dynamic range of operation, fully satisfied. From the results shown, it can be concluded that the type of burner that fully satisfies the set tasks is the optimized Burner 1.

The influence of different types of gaseous fuel on the performance of the optimized burner

One of the tasks of this work was the multi-fuel efficiency of the optimized burner. Regarding the consumption of gaseous energy sources in Serbia, natural gas is used, both domestic and imported, then liquid petroleum gas, and since one of the primary directions of energy development is the application of RES, biogas (as a representative of gaseous fuels within renewable energy sources) and its application indeed occupies an important place in energy and the development of gas devices. Natural gas in Serbia has a variable quality depending on sources and time. This is reflected in the composition of the gas, which can change significantly in a short time interval. Changes in the quality of natural gas inevitably lead to changes in many of its characteristics, which directly affects the combustion process and the operation of the burner [6]. Sudden changes in fuel quality can cause unstable burner operation, blowing-out, or flame flashback. The injector performance of an atmospheric burner is particularly sensitive to fuel quality because of the limited possibilities of regulation than burners with forced air supply [7]. In order to investigate the changes in burner performance that occur due to the quality (composition) of natural gas, several thermochemical and physical properties of gaseous fuel were varied depending on the model of the compositions.

Results and conclusion of the experimental tests

During testing with a commercial mixture of propane and butane (LPG), the optimized burner 1 fully satisfied the tasks set before the optimization methodology performed in this paper. One of the important tasks of optimizing this burner is a multi-fuel capability, *i.e.*, the operation of the burner in the prescribed operating modes when using a different type of gaseous fuel [8]. Therefore, the optimized burner 1 was experimentally tested with the following types of gaseous fuels: methane (99.5% mol CH_4, 0.5% mol N_2), natural gas (79.6% mol CH_4, 0.4% mol N_2, 20% mol CO_2), biogas (59.7% mol CH_4, 0.3% mol N_2, 40% mol CO_2). The results of these tests are shown in fig. 12.

The diagram shown in fig. 12 indicates that the CO emission does not exceed the limit value of 50 mg/kWh over the entire dynamic range of operation, while the NO_x emission is slightly higher than the limit value at lower heat powers. This was the consequence of the occurrence of sound instabilities when using these lower calorific value gaseous fuels in the range of thermal power from 30-75% [9]. Solving the problem of sound instability during the operation of the optimized burner in the combustion chamber of the reference gas device was not the subject of the optimization methodology adopted and applied in this work. Nevertheless, the results shown in fig. 12 show that at the maximum thermal power of 10.2 kW, the optimized burner 1 fully meets the requirements set during the optimization of this burner. It can be concluded that performed changes of burner design, as its optimization, have been successfully completed.

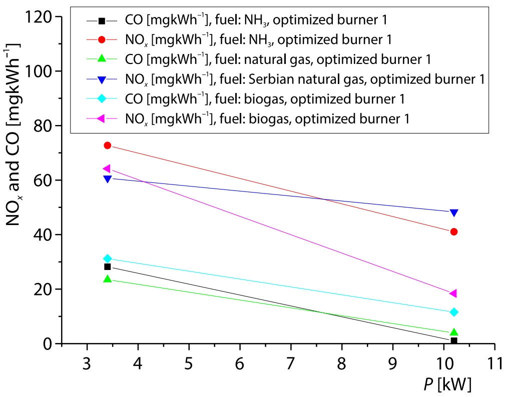

Figure 12. Emissions for different types of gaseous fuel and optimized Burner 1

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