RESEARCH AND DEVELOPMENT OF EFFICIENT, ENVIRONMENTALLY IMPROVED HOUSEHOLD GAS APPLIANCES

by

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An experimental research and analysis of performance of three domestic household gas appliances was carried out. The objective of this work, based on the conducted analysis of the research data, was to improve the appliances' performance, preferably through relative simple modifications, in order to satisfy DIN 4702 emissions and efficiency standards when using different fuels, including natural gas, liquefied petroleum gases and lower quality natural gas. This report summarizes details of this work and how the objectives were achieved.

Key words: *household gas appliances, combustion, emissions, energy efficiency, low quality natural gas*

Introduction

Household appliances are one of the main consumers of gaseous fuels. As far as natural gas (NG) is concerned, it is estimated that more than 26% of world production of NG is used in households. In Europe this figure is close to 40%. In Serbia utilization of NG is basically in industry and energy production while households consume only 15% of total NG consumed, according to data for year 2000. This unfavorable situation in Serbia has to be changed and it is planned to connect about 450,000 households to gas pipe lines until 2015. NG consumption in Serbia should reach between 6 to 7 billion cubic meters per year in 2020. It is particularly important to increase NG consumption in Serbian households in order to substitute electric energy for heating, cooking, and hot water production. Following the increase of NG consumption, which is one of the main objectives of Serbian energy strategy, it has to be followed by the decrease of specific fuel consumption including thermal efficiency increase and emissions reduction. The reduction of emissions is basically concerned with reduction of CO and NO_x but also with emission of carbon dioxide which is known to cause global warming. In addition, in particular areas of Serbia local natural gas composition can change. The content of inert components in domestic gas fields can be high, some times even 60%, of which mainly is CO_2 and to lesser extent N_2. In order to utilize this, lower quality NG, the gas companies mix it with imported natural gas, achieving NG composition in the pipe-lines at best about 85 vol.%

methane, with some small amount of higher hydrocarbons, and about 10-15% of inerts (CO_2 and N_2). This situation can cause problems for boiler operation in terms of ignition, flame instabilities, and emissions. Faculty of Mechanical Engineering in Belgrade proposed a project regarding the mentioned context which was accepted and financed by Serbian Ministry of Science and Environmental Protection. A consortium of research institutions including Faculty of Mechanical Engineering, Belgrade, Faculty of Geology and Mining, Belgrade, Mihajlo Pupin Institute, Belgrade, and industry, the gas appliances manufacturers AlfaPlam, Vranje, and Euroteh-Gas, Zrenjanin, and gas company NIS Energogas, Belgrade, participated in this three-year project. This paper summarizes main results of this project.

Project objectives

Objectives of the project include research and development, or modification of three household appliances already in production at AlfaPlam and Euroteh-Gas in order to improve their performances and satisfy DIN 4702 emissions standard, when using NG, liquefied petroleum gases (LPG), and lower quality Serbian NG [1-4].

The preliminary phase of the work was an analysis of performance of gas appliances available on Serbian market in order to establish some kind of average state-of-the-art performance for particular type of gas household appliances.

Results on investigation and analysis of performance of different appliances available on Serbian market

Table 1. Emission limit values for three European emission limit values standards

Emission [mg/kWh]	DIN 4702	Swiss	Blue Angel*
NO_x	200	80	60
CO	100	60	50

* The Blue Angel is a title of the national eco-labeling program introduced by German Government in order to promote environmental policy, both for manufacturers and consumers

Altogether performances of 22 appliances of different types and power were experimentally investigated. Investigations were performed at Mihajlo Pupin Institute. The fuel used was NG. For comparison of the performances, some of the emission limit values (ELV) standards are given in tab. 1.

Efficiency for gas boilers is min. 85%. Concerning this work DIN 4702 is accepted. The results of investigation are shown in figs. 1-3 and briefly analyzed.

As shown in fig. 1 efficiency, depending on thermal power, varied from 84 to 95% for air heaters, from 88% to 96% for combined boilers and from 90% to 93.5% for boilers. Except in one case all appliances satisfied the 85% limit of efficiency. The CO emission, fig. 2, scatters for combined boilers. It is very low, less than 10 mg/kWh for air heaters and for boilers over 60 kW. Practically all appliances satisfied 100 mgCO/kWh limit. The NO_x emission shows characteristic rise with thermal power, except for boilers over 60 kW. Most of the appliances satisfied 200 mgNO_x/kWh limit. It is interesting to note that only one gas appliance satisfied the Blue Angel limits.

Investigation and improvements of selected gas appliances manufactured in Serbia

The project participants from industry selected following gas appliances, as different, yet typical products:

(1) GAS-50 cooker, manufactured by AlfaPlam,
(2) Alfa-9 air heater, manufactured by AlfaPlam, and
(3) wall hung 12 kW boiler, manufactured by EurotehGas.

Investigation of appliances included operation stability, efficiency, and emissions of CO and NO_x. The appliances normally use commercial NG and LPG fuels.

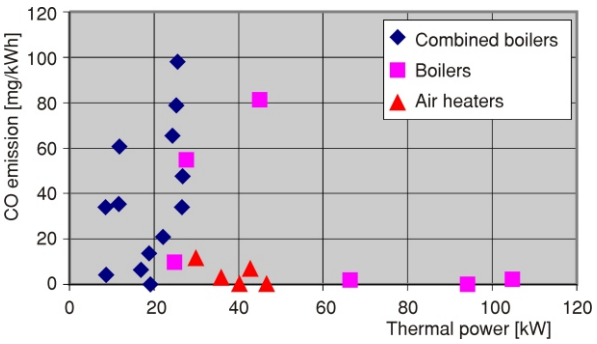

Figure1. Efficiency as a function of thermal power

GAS-50 cooker, AlfaPlam

The GAS-50 cooker stove burner is shown in fig 4. It is a classical atmospheric, substoichiometric burner.

The secondary air is introduced through purposely cut perforations in the stove walls. All emission measurements were performed using TESTO 360 gas analyzer.

Experimental investigations using LPG showed that the original (reference) burner did not comply with the ELV regarding CO, as can be seen in fig. 5.The CO emission was about 300 mg/kWh, three times the maximum allowed value. The NO_x emission was around 110 mg/kWh which was almost two times lower than ELV. The flue gas air coefficient was very high, reaching mean value of 6.2. The corresponding thermal efficiency was 74.1%.

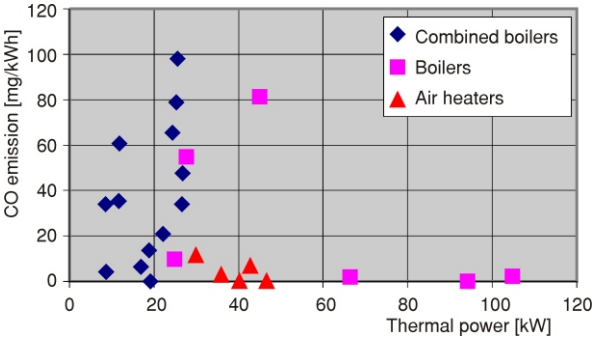

Figure 2. CO emission as a function of thermal power

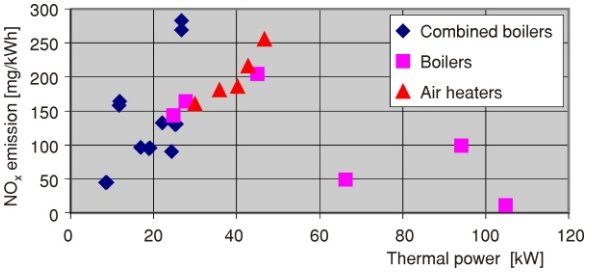

Figure 3. NO_x emission as a function of thermal power

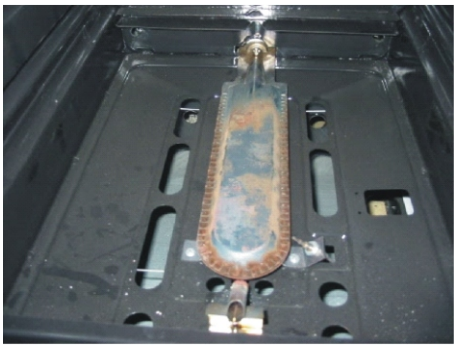

Figure 4. The stove burner

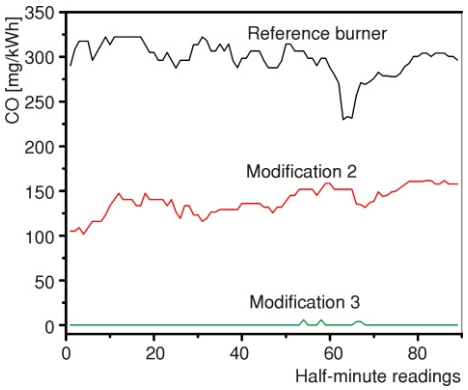

Figure 5. CO emissions for the reference burner and two burner modifications

In order to increase the thermal efficiency total air coefficient was decreased to 3.0 by decreasing chimney draught. Thus, thermal efficiency increased to 91%, which is notably higher than the limit value of 85%.

The problem of high CO emission was analyzed and solution proposed. Having in mind the real physical-time system a laminar flame front was analyzed making use of CHEMKIN and FLUENT codes for chemical kinetics and fluid dynamics.

Data on flame front structure, figs. 6 and 7 define time scales for fuel oxidation, active species and pollutants formation. In addition, characteristic CFD images of zones of formation of pollutants are shown in fig. 8. These findings enabled better understanding of pollutant formation and in turn how to improve performance of burners.

After analysis of the obtained results, modifications of the stove design were proposed and carried out. Modifications included increase of stove furnace volume and changes of burner and fuel nozzle positions. The results after modifications 2 and 3 are shown in fig. 9.

Modification 2 decreases CO emission over 2.5 times, but it is still over ELV of 100 mg/kWh.

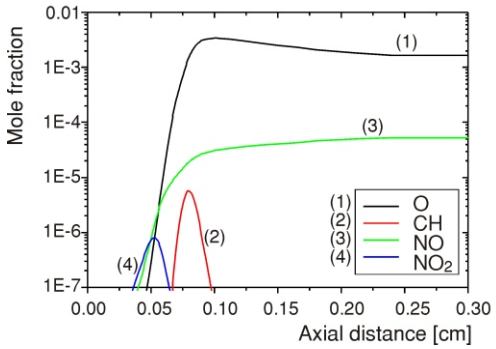

Figure 6. Selected species profiles for λ = 1.0 methane flame

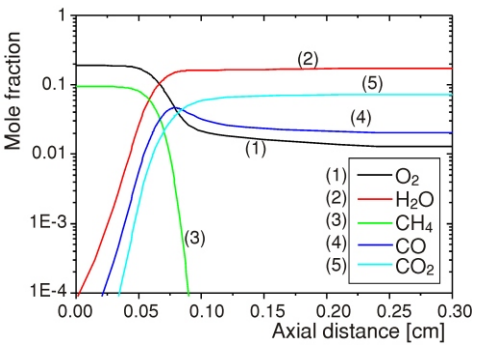

Figure 7. Selected species profiles for λ = 1.0 methane flame

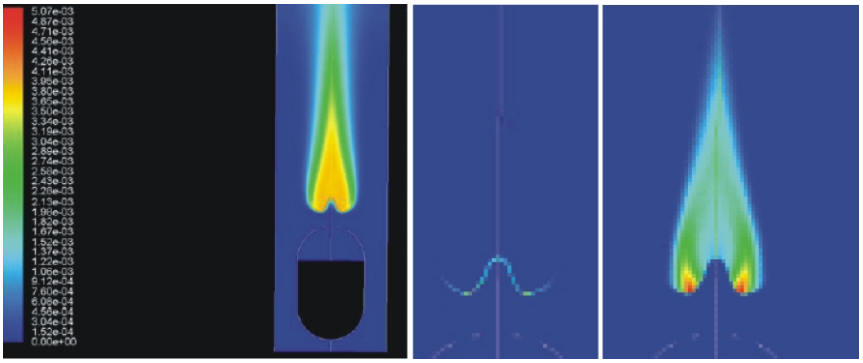

Figure 8. Rates of formation of CO, prompt and thermal NO, respectively

The NO_x emission, as expected, increases 10-15% over ELV of 200 mg/kWh.

The next modification 3 further lowers CO which is now just below the ELV. On the other hand, NO_x emission is 320 mg/kWh, which is 60% over the ELV.

After analysis of the effects of modifications on emissions and thermal efficiency the following conclusions can be drawn.

(1) The CO and NO_x emissions are practically not correlated with thermal efficiency.
(2) Stove modifications substantially affect the CO and NO_x emissions.
(3) Modifications of the cooker draught affect thermal efficiency.

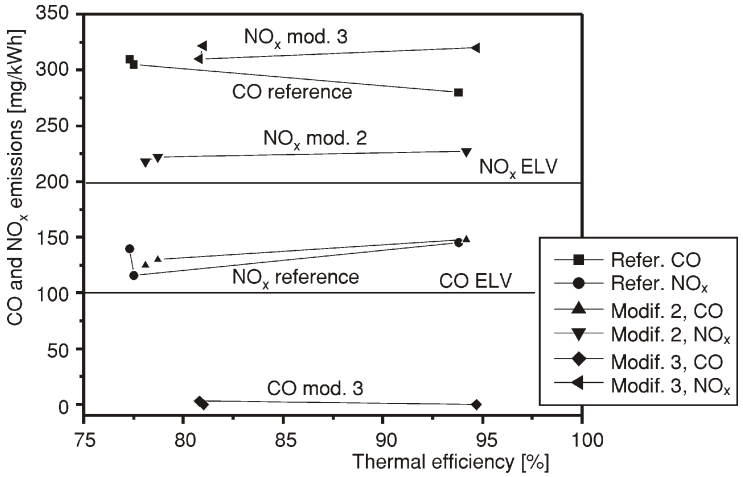

Figure 9. CO and NO_x emissions as a function of thermal efficiency of the cooker

The improvement of CO emission resulted in increase of NO_x emission over ELV. New modification, this time, by optimizing fuel nozzle, decreased NO_x emission below the ELV, figs. 10 and 11.

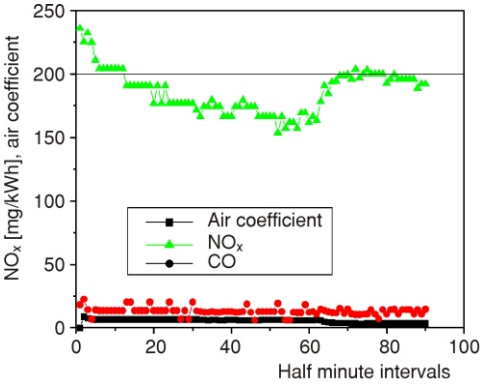

Figure 10. NO_x emission and air coefficient

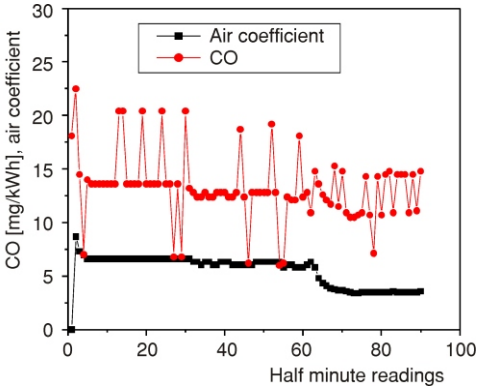

Figure 11. CO emissions and air coefficient

Thus, in step-by-step modifications, the GAS-50 cooker performances were improved, and the objectives were achieved:

– increased energy efficiency,
– satisfied thermal efficiency limit value, and
– satisfied CO and NO_x emissions limit values.

ALFA 9 air heater AlfaPlam

ALFA 9 air heater is intended for use in households. Nominal heating power is 9 kW and nominal thermal efficiency is 84%. The heater can use NG and LPG fuels via one Worgas atmospheric burner. The secondary air is brought into the flame through side air openings. The heater and burner are shown at figs. 12 and 13, respectively.

Experimental investigation was performed using LPG, NG, and combinations of LPG/CO_2 and NG/CO_2 in order to model Serbian lower quality NG fuels, at nominal power. The concentrations of CO_2 were varied from 0-47 vol.%. For the limit value that corresponds to fuel quality variations found in Serbia 20 vol.% of CO_2 in fuel was assumed.

Flame images, fig.14, show characteristic flame geometry without and with CO_2 in LPG. At CO_2 41.4% the flame lift and partial blow-out can be noticed.

The results of CO and NO_x emissions of ALFA 9 air heater, fueled with LPG and LPG/ CO_2 mixtures, are shown in fig.15.

Figure 12. ALFA 9 air heater AlfaPlam

Figure 13. Worgas burner

Figure 14. Flame geometry, CO_2 = 0% (left) and CO_2 = 41.4% (right)

Figure 15 shows that CO and NO_x emissions comply with the ELVs, except for CO_2 content over 43% when CO gets higher than ELV. The general behavior of CO and NO_x is as expected, especially for NO_x, the gradual decrease behavior.

Regarding thermal efficiency of the heater, the measured value was 85.6% which is slightly higher than the minimum limit value of 85%. With the introduction of CO_2 in the fuel the efficiency decreases to 79.4% at CO_2 content of 23%. This is due to the increase of air coefficient from 1.9 for CO_2 0% to 2.6 for CO_2 23% and other effects.

Besides affecting emissions and efficiency, presence of CO_2 influences pilot flame, flame spreading over the burner mantle, and flame stability. All these effects were such that the operation of heater was impossible. These problems were solved by redesigning of the pilot flame system and by introducing turbulizers on the mantle. These changes in design did not influence emissions of the burner.

The experimental research was conducted using NG and NG/CO_2 mixtures as well.

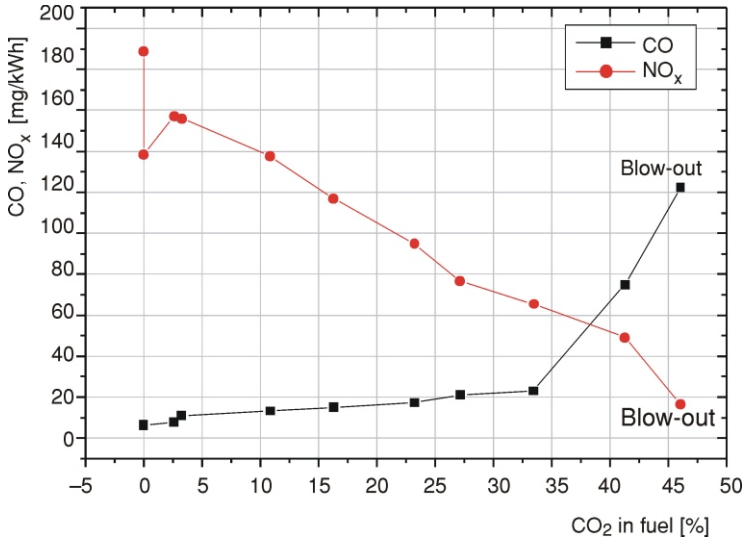

Figure 15. CO and NO_x emissions as a function of CO_2 content in fuel

The results, fig. 16, demonstrate similar behavior as when fueled with LPG, fig. 15, except that in general, NO_x emission is lower, while CO is higher. Both CO and NO_x emissions comply with ELVs.

Thermal efficiency was almost the same as in the LPG case, decreasing from 85.6% to 80.5%.

The performed research, analysis and redesign enabled ALFA 9 air heater AlfaPlam to be stable and to comply with ELVs for CO and NO_x when fueled with NG, LPG, and lower quality Serbian natural gas.

Wall-mounted, combined 12 kW, C-type boiler of EurotehGas

Wall-mounted, combined 12 kW boiler is used for household heating and hot water production. The boiler can burn commercial NG and LPG fuels. Figure 17 shows a photograph of boiler's combustion chamber and burner.

The combustion system is modular, consisting of identical atmospheric burners with primary aeration. Secondary air is provided by purposely designed openings at the bottom of the combustion chamber.

Experimental research of boiler performance showed that at nominal thermal power, when operating on LPG, it was not possible to achieve ELVs for both pollutants, CO and NO_x. After analysis of the obtained results and combustor characteristics the fuel

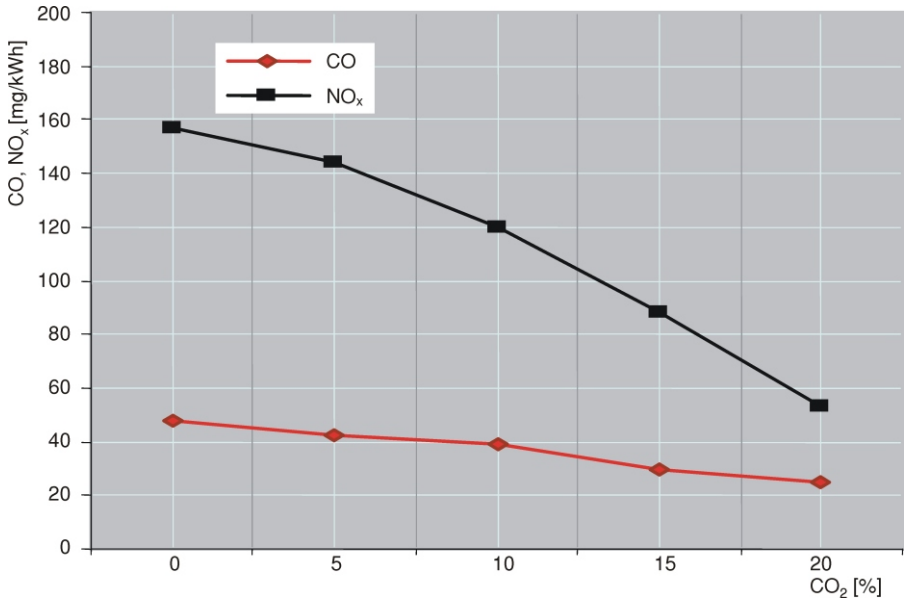

Figure 16. CO and NO_x emissions as a function of CO_2 content in fuel

nozzle and its position were optimized. As a result, CO emission decreased substantially below ELV while NO_x emission decreased, but still was over ELV.

Next step was to optimize burner. Having in mind that it was not possible to redesign the mantle and flame ports, the NO_x emission control was performed by optimizing flame port loading. It was experimentally found that the port loading should decrease at least 21.7%. In principle it is possible to achieve this by a number of actions, such as, to decrease the thermal power from 12 to 9.4 kW while keeping the existing burner module, or to increase flame ports area, or to increase number of burner units. The only realistic solution in this case was the first one, power decrease. As a result, for thermal power of 9.4 kW, the NO_x emission dropped to 185 mg/kWh which is below the ELV of 200 mg/kWh.

Figure 17. Combustion chamber and burner

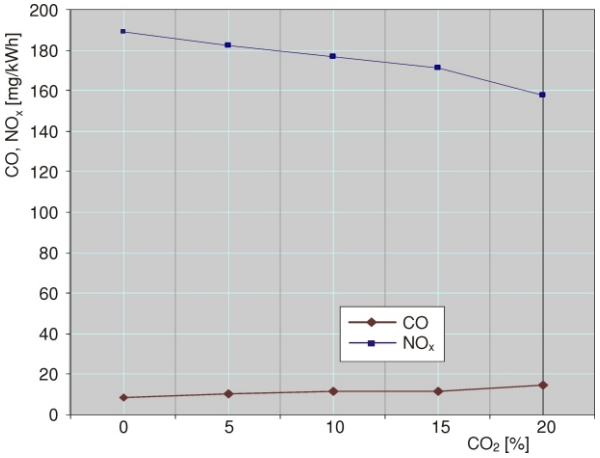

Figure 18. CO and NO_x emissions as a function of CO_2 content in fuel

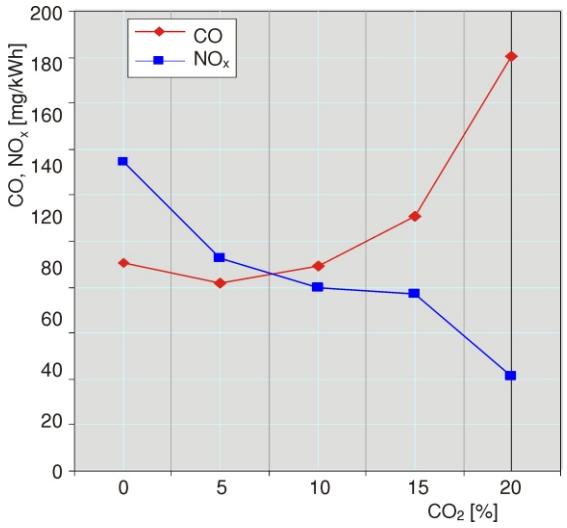

Figure 19. CO and NO_x emissions as a function of CO_2 content in fuel

Regarding efficiency, for 9.4 kW power, the measured boiler efficiency was 86.2% which is satisfactory, being over the limit of 85%.

Thus, by redesigning and readjustment of burner and fuel injector and decreasing flame port loading the boiler satisfied the ELVs as defined by DIN 4702.

After that the boiler performances were analyzed at 8.2 kW, fueled with LPG/CO_2 mixture. It can be seen, from fig. 18, that with the increase of CO_2 the NO_x emission decreases while CO has slight rise. But in general, the boiler complies with the ELVs. The thermal power continuously decreases as the fuel flow rate being kept constant.

The efficiency, basically being 85.6%, rises with the rise of CO_2 content in fuel.

The next step was to perform research using NG and CO_2 as a fuel, with redesigned burner and fuel injector. As expected, CO increases while NO_x decreases with the increase of CO_2 (see fig. 19). The boiler complies with ELV for NO_x in the whole range of carbon dioxide content in fuel while the CO emission only up to 12.5% of CO_2.

In order to solve the problem of CO emission further optimization of boiler was conducted. As it was not allowed to redesign burner mantle and the perforation pattern, the optimization was done by changing the flame port loading, as in the case with LPG. Figure 20 shows CO and NO_x emissions as a function of CO_2 content in fuel. Clearly, the emissions of CO and NO_x comply with the ELVs in the whole range of the carbon dioxide content.

Regarding efficiency, it decreases from slightly over 85% to 82%. By controlling chimney draught it was possible to keep the efficiency over 85% while little affecting the emissions.

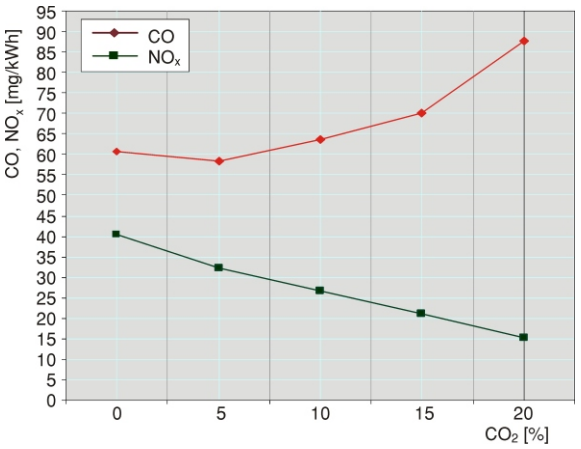

Figure 20. CO and NO_x emissions as a function of CO_2 content in fuel

Conclusions

Performances of 22 household gas appliances of different types and power available in the Serbian market were experimentally investigated and analyzed in terms of efficiency and CO and NO_x emissions.

Three selected gas appliances from production program of the project participants from industry, AlfaPlam, Vranje, and EurotehGas, Zrenjanin, (cooker, air heater and combined boiler) were selected as the project research objects. Their performances were experimentally investigated, analyzed in terms of operation stability, efficiency and CO and NO_x emissions when fueled with natural gas, liquefied petroleum gases and low quality natural gas.

Main objective of the project was modification of the chosen household appliances in order to improve their performance and satisfy DIN 4702 emissions and efficiency standard.

The objectives of this work were successfully fulfilled.

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