Technical and environmental performance of 10 kW understocker boiler during combustion of biomass and conventional fuels

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Abstract. This paper treats about the impact fuels from biomass wastes and coal combustion on a small boiler operation and the emission of pollutants in this process. Tests were performed in laboratory conditions on a water boiler with retort furnace and the capacity of 10 kW. Fuels from sewage sludge and agriculture wastes (PBZ fuel) and a blend of coal with laying hens mature (CLHM) were taken into account. The results in emission changes of NOx, CO_2, CO and SO_2 and operating parameters of the tested boiler during combustion were investigated. The obtained results were compared with corresponding results of flame coal (GFC). Combustion of the PBZ fuel turned out to be a stable process in the tested boiler but the thermal output has decreased in about 30% compared to coal combustion, while CO and NO_x emission has increased. Similar effect was observed when 15% of the poultry litter was added to the coal. In this case thermal output has also decreased (in about 20%) and increase of CO and NOx emission was observed. As a conclusion, it can be stated that more effective control system with an adaptive air regulation and a modified heat exchanger could be useful in order to achieve the nominal power of the tested boiler.

1 Introduction

In Poland, coal is still the primary heat source, both in the industrial and private sectors. Sustained need for this kind of energy source results from economic and social factors, mainly the relation between the competitive price and quality in terms of energetic potential, domestic availability of relatively shallows deposits and well-developed mining infrastructure. The long-term history of coal consumption in Poland results in most of the operated small scale technical facilities being adopted to its combustion.

Despite of the aforementioned consideration, in recent years there has been an evident change in the approach to energy management and sources. More attention is paid to the use of renewable energy as the source, which may prevent from the environmental damage resulting from the use of fossil fuels, in particular the coal. The main source of renewable energy is the biomass, which represents 80% of the renewable energy on the Polish market [1]. In energy processing the most popular are forest residues and agricultural products specially grown for this purpose (corn, sugar beets, canola, oats, etc.) [2,3]. However, the use of unclassified assortments of cereals or grains as well as livestock residues and sewage sludge produced in wastewater treatment, may become an interesting thermochemical conversion target [4,5].

Biomass renewable energy production trends mentioned

above, forces national boiler manufacturers to offer a large range of equipment for domestic use designed only for biomass utilization or multi-fuel boilers with the possibility of burning coal and biomass separately or in co-combustion manner. This multi-fuel thermal conversion is also used in existing poorly controlled stoves and boilers. Data on the biomass thermal treatment in this kind of devices, regarding their energetic sustainability and environmental impact, are still insufficient.

Although the research on woody and agricultural biomass combustion and co-firing in small scale units has been widely reported in literature. For example authors presented testes of combustion agriculture wastes such as: sunflower husk, sugar can, nut shells [6] and coffee ground [7] in small scale boilers. Additional in literature [8] can be found information about modeling gaseous emissions during combustion of agriculture wastes in small scale boilers.

There are only few publications on the scope of livestock waste and sewage sludge. Allouis et al. [9] investigated the co-combustion of pelletized poultry manure waste with olive pomace in a 50 kW burner installed in a water-cooled fire-place. Whereas, Krugly et al. [10] discussed burning of the sewage sludge pellets in a commercial 13 kW pellet boiler.

Therefore, the main aim of this research is to investigate the feasibility of burning or co-burning of the biomass, less commonly processed in household heat production.

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Emphasis is put on identification of the main design and operational parameters and their improvements as well as the environmental impact they may have. The combustion tests were performed in a laboratory conditions, on a water boiler with retort furnace with a capacity of 10 kW designed for coal or biomass burning.

2 Materials and methods

2.1 Fuel characterization and thermogravimetric experiments

The combustion tests were performed with the gas-flame coal (GFC) as a reference fuel, blends of sewage sludge, agriculture waste (named PBZ), and blends of coal with laying hens manure (CLHM).

The gas-flame coal was provided by Polish mine KWK Bobrek-Piekary. The PBZ fuel was made of the communal sewage sludge, a product from a mechanical and biological wastewater treatment plant located in Opole, south part of Poland, and the unclassified oats grain from farm located in Krapkowice. The laying hens manure was collected from the poultry farm located in Wlostowa, Opole district.

The fuels were sampled and analyzed in accordance with the relevant EU standard methods for the biomass samples, and national standards for coal (Table 1). Fuel parameters were determined in Laboratory for Instrumental Analysis in Environmental Engineering and Energetics located at the Opole Technical University.

Table 1. Standards for fuels analysis.

Parameter	Coal	Biomass
Moisture	PN-80/G-04511	PN-EN ISO 18134
Volatile matter	PN-G-04516	PN-EN ISO 18123
Fixed carbon	calculated by difference	calculated by difference
Ash	PN-ISO 117 (at 550 ^{o}C)	PN-EN ISO 18122
Carbon	PN-EN ISO 16948	PN-G-04571
Hydrogen	PN-EN ISO 16948	PN-G-04571
Sulphur	PN-EN ISO 16994	PN-G-04584
Nitrogen	PN-EN ISO 16948	PN-G-04571
Oxygen	calculated by difference	calculated by difference
Higher heating value	PN-ISO 1928	PN-EN 14918
Lower heating value	calculated	calculated

The thermogravimetric TG measurements were performed on the NETZSCH STA F3 Jupiter device. The fuel amount of 20 ± 0.1 mg was heated in Al_2O_3 crucible from 293 K to 1273 K at 10 K/min heating rate.

The protective and purge gas was high purity air, and its flow rates were 20 and 50 mL/min, respectively. All the tests were carried out three times to ensure the reproducibility of the results.

2.2 Combustion testes in a small scale boiler

The research was performed on commercially available ERK water understocker furnace boiler of 10 kW nominal capacity, designed for burning coal or biomass. The unit was installed at the test stand located in Combustion Technology Laboratory being a part of The Department of Thermal Engineering and Industrial Facilities at Opole University of Technology (50.652 ^{o}N, 17.902 ^{o}E). The schematic layout of the experimental setup is presented in Fig. 1.

The setup, in accordance with the EN 303-5 standard, included several connected functional units allowing to perform boiler test under specific conditions. The equipment used for testing incorporated the following: investigated boiler (1), piping system, water storage tank (2), variable speed pump (3), three-way control value (4) with microprocessor controller, heat exchanger (5) with radiators dissipating the heat outside, and measurement devices.

Paired PT100 resistive sensors were used to measure water outlet (T_o) and return (T_r) temperature, whereas Apator Powogaz vane-wheel meter was used to measure water flow (F). Based on the herein mentioned indicators boiler's power was determined with the heat meter (6). Gaseous compounds concentration (O_2, CO, CO_2, NO_x and SO_2) in the flue gas was continuously measured with the Madur portable emission monitoring system including the conditioner unit PGD-100 (7) and the Photon gas analyser (8) calibrated with appropriate gas. The temperature between the furnace and the deflector was measured with a portable DelthaOHM HD2107.2 temperature recorder coupled with N-type thermocouple. Table 2 shows the specification of the equipment used during the test. Boiler's efficiency was calculated with the indirect method presented in [11].

The flame-gas coal GFC delivered in separate bags was scattered, mixed and left for several days in the laboratory to unify moisture content. The pre-drayed coal was mixed with the poultry manure in 1:0.176 proportions not being formed to obtain the CLHM fuel. Whereas the PBZ was formed from sewage sludge and unclassified oats grain in the 1:0.25 proportion [12].

Granulation of the obtained biomass fuels met the requirements of the fuels for the tested boiler.

The burner, heat exchanger and fuel tank were cleaned before each test to unify the initial conditions.

The electronically controlled pump provided a steady water flow, whereas the three-way valve with controller ensured stability of the return water temperature standing as 55°C. When the fire-up phase was completed, the fuel feed rate and combustion air flow were changed until the power was as nearest to its nominal value as possible and the emission reached the lowest level.
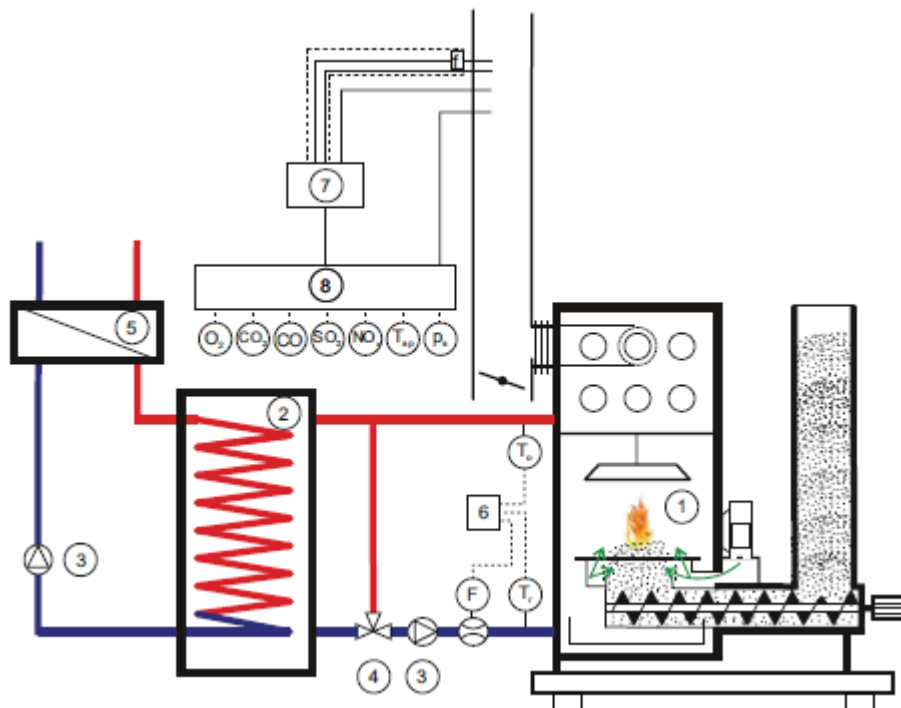
Fig. 1. Scheme of the experimental setup.

Table 2. Specification of the monitoring equipment.

Parameter	Method	Unit	Range	Accuracy	Resolution
O_2	Electrochemical sensor	%	$0 \div 21$	+/- 0.01 abs. or 5 rel.	0.01
CO_2	NDIR detector	%	$0 \div 25$	+/- 0.1 abs. or 4 rel.	0.01
CO	NDIR detector	ppm	$0 \div 20{,}000$	+/- 4 abs. or 4 rel.	1
NO	NDIR detector	ppm	$0 \div 5{,}000$	+/- 5 abs. or 5 rel.	1
NO_2	NDIR detector	ppm	$0 \div 1{,}000$	+/- 5 abs. or 5 rel.	1
SO_2	NDIR detector	ppm	$0 \div 5{,}000$	+/- 5 abs. or 5 rel.	1
Flu gas temperature	K-type thermocouple	ºC	$-10 \div 1{,}000$	+/- 2	1
Combustion chamber temp.	N-type thermocouple	ºC	$0 \div 1{,}250$	+/- 1.5	1
Water temperature	PT100 resistive sensor	ºC	$0 \div 150$	+/- 0.4	0.1
Water flow rate	Vane-wheel	m^3/h	$0.24 \div 6.0$	3*	0.005

* – for hot water, abs. – absolute, rel. – relative.

3 Results and discussion

3.1 Fuel characteristics

The tests were conducted on three different fuels with various ranges of physicochemical parameters as shown in Table 3. As a main approach in this study it was assumed that the reference fuel would be the bituminous coal, as recommended for this type of boiler. According to the manufacturer's guidelines, the device is also suitable for biomass combustion, therefore capabilities of co-burning of coal with the addition of waste biomass, as well as combustion of raw biomass wastes have been tested. Regarding the coal and poultry manure blend, the biomass content was at the level of 15%, to emphasize some mechanisms occurring during the co-combustion process. This share is somewhat more than 10%, i.e. the amount more practically recommended for co-burning [13].

Generally, it is well known that fuel parameters deeply affect combustion process. 10% moisture content was at the similar level in all the tested fuels therefore it should not have a leading role in the process. Whereas the remaining physicochemical parameters of the fuels varied significantly. The lowest, i.e. 6.9% ash content was observed in burned coal, addition of poultry manure to the GFC increased the amount of the ash to about 10%, whereas PBZ was the highest ash fuel with about 20% of mineral matter. The inorganic matter affects the combustion profiles but it may also cause problems with the slagging and effective removal [14]. The carbon content is related to the calorific value [15], and is the determinant of energy concentration. Both parameters were the highest for coal, while addition of waste biomass led to a noticeable decrease in the C and LHV value. The content of other macro elements in the fuel results in a formation of toxic compounds in the combustion process. Particular attention was paid to the presence of nitrogen and sulfur in fuels as they are closely related to the mechanisms of NO_x and SO_2 formation in furnace [14,16] and their emission to the atmosphere, especially in terms of legal requirements.

Among the tested fuels, the GFC contained the lowest amount of N (i.e. 1.50%), while the PBZ contained much more N than the other fuels (3.89%). Regarding the S content, tendencies of these parameters were reversed. Application of temperature-controlled combustion along with the thermogravimetry on a microscale provided valuable hints on how to increase combustion efficiency as well as how to improve boilers' design and maintenance. Fig. 2 shows that profile of weight loss rate during coal combustion differs significantly from the one of a biomass as a result of different proportions between the volatile matter and fixed carbon of those fuels. In case of coal combustion one of the stages observed (Table 4. Stage II), indicates that released volatile matter passes fluently into the char combustion. However, co-combustion with a certain amount of poultry litter takes place in two stages (Table 4, Stage I and II), which is appropriate for the biomass. The DTG profile for PBZ is typical for the waste biomass combustion with a distinct separate peak for calcium carbonate decomposition (Table 4, Stage III) [17].

The ignition temperature T_i of CLHM is lower than the one of GFC, due the biomass presence in the blend

Table 3. Fuels parameters (air dried basis).

Parameter	Unit	GFC	LHM	PBZ
Moisture	wt. %	7.93	12.18	10.5
Volatile matter	wt. %	31.47	58.85	41.35
Fixed carbon	wt. %	53.7	3.22	28.28
Ash	wt. %	6.9	25.75	19.87
Carbon	wt. %	69.46	33.72	34.10
Hydrogen	wt. %	4.67	5.19	4.23
Sulphur	wt. %	0.53	0.39	0.11
Nitrogen	wt. %	1.50	3.68	3.89
Oxygen	wt. %	9.01	19.09	27.23
Higher heating value	MJ/kg	27.650	13.772	16.128
Lower heating value	MJ/kg	26.458	12.356	14.949

wt % - weight percent
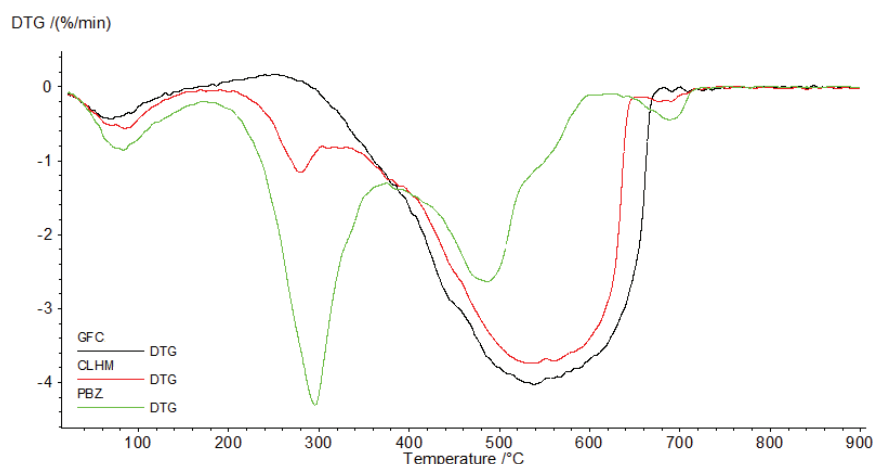
Fig. 2. Derivative thermogravimetric (DTG) curves of tested fuels.

Table 4. Parameters of combustion.

Sample	T_i	T_b	t_b	Stage I		Stage II		Stage III	
				DTG I	T I	DTG II	T II	DTG III	T III
	°C	°C	min	%/min	°C	%/min	°C	%/min	°C
GFC	404	685	28	-	-	-4.00	536.2	-	-
CLHM	249	656	41	-1.16	279.1	-3.72	536.3	-0.19	685.2
PZB	254	627	36	-4.30	295.5	-2.64	486.1	-044	688.3

T_i – ignition temperature,

T_b – final temperature of char combustion,

t_b – total combustion time.

and its early devolatilization. Therefore, addition of the biomass could be in favor of coal ignition initiation, but in practice in the operated units, the early release of volatile matter has led to uncontrolled combustion at low temperatures [13].

It must also be taken into consideration also, that the maximal loss rates DTG_{max} for coal (Stage II, Table 4) occured in higher temperatures, while for the biomass it took place at the devolatilization stage (Stage I, Table 4). High reactivity of the biomass, results in faster and more intensive burning of this material, than in case of the coal, and as a consequence leads to uneven fuel bed burning. In the operation of large industrial boilers, separate fuel delivery systems are used to offset the effect. Regarding the automatic small scale boilers, the fuel rate is controlled by the working period of the feeder. Those inappropriate interval adjustments create difficulties during conventional operation, especially in case of combustion blends such as the CLHM. Increased unburned organic matter in the bottom ash or "crater" combustion are examples of wrong fuel feeding settings.

3.2 Boiler technology

The first objective of the boiler test was to observe the settings of the feeder operating parameters to achieve thermal output with fixed fuel as closest to the nominal value as possible. In case of the coal as the reference fuel the on/off working periods were 3/27 s, which

corresponds to fuel mass flow of 1.50 kg/s, with boiler performance being very close to the nominal value (Table 5). However, addition of 15% of the livestock waste biomass, having considerably different bulk density, changed the fuel mass flow and consequently energy input to the boiler. As a result, during CLHM tests the boiler was performing at the 71% load. The mass flow of the PBZ was changed significantly, but it only reached the 51% load. Attempts to increase the amount of fuel caused problems described in more detail in section 3.1, i.e. large loss of ignition matter in the bottom ash for CLHM, and unstable fire bed for PBZ, which led to unexpected shutdown of the boiler.

The flue gas temperature during coal combustion and coal with poultry manure co-firing, increased significantly to 200 °C, resulting in a high physical energy heat loss, at the level of 17% for the GFC, and 20% in case of the CLHM. This indicates, the need to change the design of the heat exchanger to increase heat transfer.

Furthermore, the tested boiler is of a compact size and a horizontal heat exchanger at the top, where considerable quantity of the fly ash is deposited, reducing the heat transfer. Both combustion and co-firing attempts occurred with no ash lumping on the burner and no slagging and the bottom ash was quite fine. However, the combustion of the PBZ with large amount of the ash caused its excessive accumulation in the ash box and limited boiler's operation time.

Table 5. Selected operating parameters for each fuel in the best conditions obtained.

Parameter	Unit	GFC	CLHM	PBZ
Feed mass flow	kg/h	1.50	1.34	1.69
On/off working period	s	3/27	3/24	6/22
Excess air ratio*, λ	-	2.00 (0.11)	2.49 (0.24)	2.72 (0.32)
Combustion chamber temp.*	°C	802 (43)	770 (46)	703 (59)
Flue-gas temperature*	°C	233 (3)	212 (7)	161 (2)
Inlet water temperature*	°C	59 (1)	59 (1)	58 (1)
Outlet water temperature*	°C	67 (1)	65 (1)	63 (1)
Thermal output*	kW_{th}	9.0 (0.7)	7.1 (0.6)	5.9 (0.4)

* average values with standard deviations

3.3 Gaseous emissions and boiler's efficiency

Arrangement of the combustion process to achieve appropriate emission level (it mainly concerns the CO and NO_x), when increasing to the maximum boiler's, is based on certain principles. The main techniques are: sufficient air excess delivery and high combustion temperature reasurance, appropriate mixing between the fuel and the air, but also proper air distribution, which are often emphasized during biomass combustion in low power boilers [14-16,18].

The tested boiler, as low-budget device has been equipment only with primary air distribution system. The most beneficial excess air ratio was obtained manually with the use of a single fan, unfortunately it was impossible to apply more advanced air control system. As it is shown in Table 4 and Table 6 the obtained average λ ratios corresponding to minimum average values of CO reached 2.00, 2.49 and 2.79 during combustion of the GFC, CLHM and the PBZ respectively. Regarding coal combustion the average CO emission (591 mg/Nm^3 at 10% O_2 in dry gas) has met the requirements of EN 303-5 standard for automatic Class 4 boiler for fossil fuel. The CO emission for the CLHM, although twice as higher as the one for coal, has also met those requirements. PBZ combustion gave visibly higher CO values, at the level of around 1,400 mg/Nm^3 at 10% O_2 d.g., yet still much lower as reported by Krugly [10] for pellet sewage sludge combustion 13,698 $\pm$ 6,762 mg/Nm^3.

Regarding the operation more valuable information is shown in Fig. 4. The CO emission during GFC combustion has changed significantly in relatively narrow range of excess air ratio, whereas during the co-firing and raw biomass combustion CO fluctuations were more intense in a wider range of λ values. There may be few explanations of this phenomenon: (a) the combustion chamber (i.e. size, shape and wall material) was designed for coal, addition of highly volatile and less energetics biomass changed the burning profile and

temperature significantly; (b) lack of secondary air distribution system, prevented good mixing of flue gases with air and effective oxidation; (c) control system based on discrete on-off regulation, without possibilities to adjust the amount of excess combustion air or fuel.

The NO_x emissions from automatically fired biomass boilers are subject to legal restrictions only in Austria, while in the Netherlands and Great Brittan the NO_x have only been limited for boiler's subsidies. The Ecodesign regulation for domestic boilers (in force in the EU from 2020), will limit the NO_x emission to 200 mg/m^3 and 350 mg/m^3 for biomass and the fossil fuel boilers respectively. As it is shown in Table 6, the analyzed boiler does not currently meet those requirements.

As stated in Fig. 5 the highest NO_x emission were observed for the PBZ, the N-richest fuel. As expected, the Fuel-NO_x mechanism was the main source in NO_x formation, which confirms the combustion temperatures below 800 ℃ in each test. Also the NO_x/Fuel-N conversion rates (CR) were 5.7%, 4.7% and 2.1% for the GFC, CLHM and the PBZ respectively. The CR decreasing tendency with lowering nitrogen bound in the fuel is often reported [6,8] and could be explained based on the Fuel-NO_x formation mechanism. Confirmation of the dominant role of this mechanism during the tests, allows to introduce certain technologies or fuels which may limit the said mechanism, i.e. air staging or flue gas recirculation.

The SO_2 emission is a result of fuel sulfur oxidation [15]. The SO_2 levels obtained during PBZ combustion were visibly lower than those of the other fuels, due to the S content in the fuel. The fuel-S to SO_2 conversion rates were relatively low 52%, 47% and 61% for combustion of the GFC, CLHM and the PBZ respectively, therefore part of the fuel sulfur remains as solid compound in the ash. This effect can be explained by the low temperature regime in the combustion chamber and in the bottom ash. Similar results were also obtained during combustion of fuel based on sewage sludge and coal slime [19].

Table 6. Flue gas composition* and loss of ignition matter in the bottom ash

Parameter	Unit	GFC	CLHM	PBZ
O_2	vol. % d.g.	10.95 (0.52)	12.93 (0.74)	13.4 (0.87)
CO_2	vol. % d.g.	9.41 (0.50)	7.61 (0.69)	7.78 (0.77)
CO	mg/Nm^3 (10% O_2 d.g.)	591 (190)	945 (271)	1139 (339)
NO_x	mg/Nm^3 (10% O_2 d.g.)	388 (20)	433 (32)	796 (65)
SO_2	mg/Nm^3 (10% O_2 d.g.)	772 (30)	733 (46)	371 (12)
Solid unburned matter	kg/kg solid residue	0.0571	0.1032	0.2014

* - average values with standard deviations
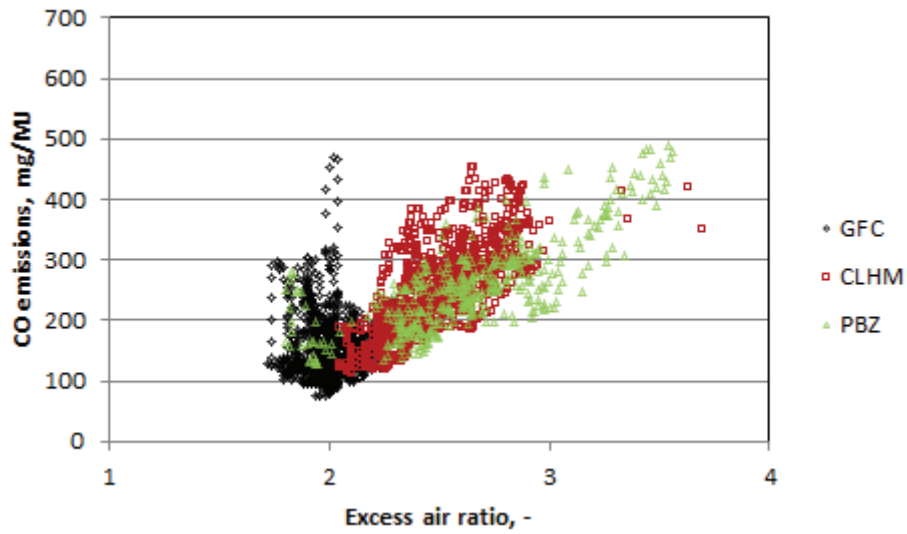
d.g. – dry gas

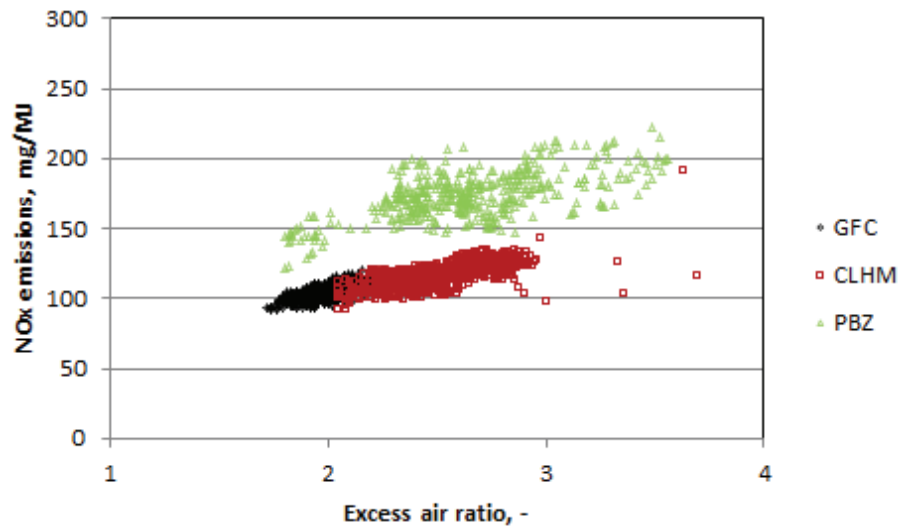**Fig. 4.** CO emissions vs excess air ratio.

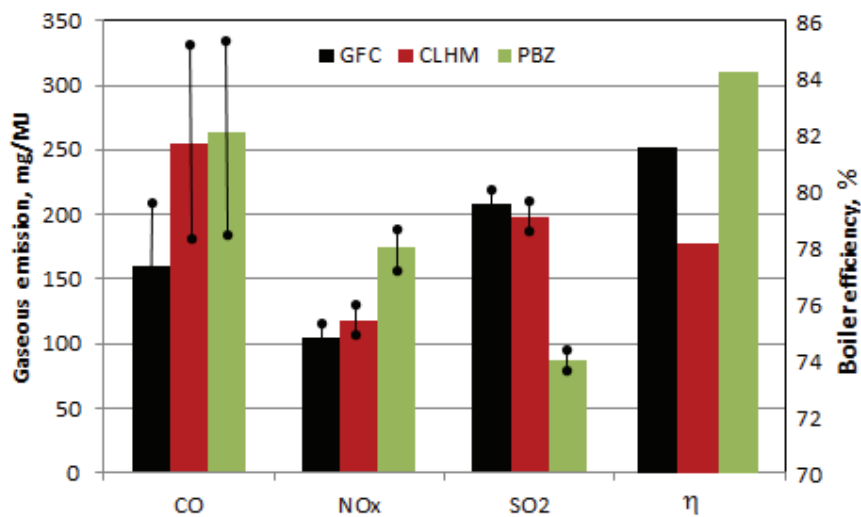**Fig. 5.** NO$_x$ emissions vs excess air ratio.

Fig. 6. Specific gaseous emissions (average values with standard deviations) and thermal efficiency.

As presented in Fig. 6 boiler's efficiency was 81.5% for the GFC, 78.1% for the CLHM, and 84.2% during the PBZ combustion. It must be clearly stated that among the researched fuel's combustion only the coal could fulfill manufacturer's guidelines in terms of nominal power.

5 Conclusions

Based on the obtained results and preceding discussion, the main conclusions can be formulated:
- the physicochemical properties of the prepared fuels differ from one another, which is reflected in various combustion profiles affecting the combustion process in the investigated boiler,
- the tested multi-fuel boiler achieved the nominal power only during coal combustion, where the CO emission and efficiency met the requirements for Class 4 Boiler according to the EN 303-5:2012 standard,
- more effective control system, with adaptive air regulation and modified heat exchanger with automatic cleaning, should improve classification performance,
- the addition of 15% poultry litter to the coal imposed changes in the fuel and air feeding, causing a decrease in thermal output (with about 20%) as well as increase in CO and NO_x emissions. Improvement of these parameters requires changes in the combustion chamber and more advanced air distribution system,
- blend of sewage sludge with oats grain in the form of granules could provide a stable combustion in the tested boiler, yet the thermal output has decreased with about 30% compared to the one obtained from coal burning, but also CO and NO_x emissions increased significantly. The PBZ combustion in the subject unit requires changes not only in the combustion chamber itself (mainly related to the increase of the combustion temperature and better air flow to mix flue gas) and its operation but also system for automatic bottom ash removal.

The presented results cover certain range of technical and environmental issues related to combustion and co-combustion of the biomass waste with coal in a small scale boiler, but it must be clearly stated, that full adaptation of this type of fuels requires analysis of the pollution emission on a broader scale, e.g. HCl, HF or NH_3.

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