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Modifications Concerning the Combustion Air from the Pyrolysis Boiler

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1. Introduction

A boiler or a stove is a device, which is used as an economical and environmentally friendly source in order to heat a place. As a fuel, biomass (wood, wood waste, straw, hay, shavings, chippings, cuttings, saw dust, etc.), fossil fuels (coal, petroleum derivates, gas), and others are used. The operation of boilers can be either fully automated, which is considered to be a great advantage just in time when we cannot control the device, or manual, which means that an operator needs to have a possibility of manual control of fuel feeding [1]. Boilers that burn and gasify lump wood are called wood gasification boilers. These devices are also used for the combustion of biomass, mostly hard dry wood (beech, oak).

Wet wood is not very suitable because it burns poorly, which causes considerable losses, and if water vapour condenses on interior parts of the device, this may lead to corrosion and device failure. The moisture content of wood billets for heating purposes should not exceed 20%; nevertheless, every boiler manufacturer demonstrates this value in product user manuals, so it is recommended to follow the instructions of the manufacturer [2]. If wood is dry enough to burn, it can generate considerable heat. A consequent reduction in the amount of air to the boiler would probably cause higher tarring; to prevent that, many users keep the fire burning by using extra-dry firewood [3]. The use of a particular type of biomass depends on its chemical and physical properties. Biomass materials can have a wide range of moisture content. High water content in fuels tends to increase the consumption of energy that is required to evaporate the water. The high moisture of biofuels has a negative impact on formation of an arch in fuel storage bins, flue gas volume, amount of water vapour in the flue gas, flue gas dew point temperature increase, and on an increased risk of corrosion on some parts of combustion equipment. This is reflected in the combustion equipment design.

The elemental composition of biomass is not very different from that of other solid fuels. The most important task is to monitor carbon, hydrogen and oxygen proportions in dry matter [4]. In contrast to fossil fuels, biomass contains about twice the amount of oxygen (O_2) and smaller amount of carbon (C). The contents of hydrogen (H_2) and nitrogen (N_2) of fosil fuels and biomass are almost the same. With regard to chemical components, biomass contains also trace amounts of elements that influence the production of combustion pollutants. They are sulphur (S) and chlorine (Cl) [5]. Individual fuels differ from each other in the content of substances influencing the production of emissions. As compared to fossil fuels, biomass has a very low sulphur content, which has an impact on the total amount of sulphur dioxide; this causes acid rain and smog episodes in villages. Chlorine, if burnt, contributes to the formation of hydrochlorid acid (HCl) and dioxins (PCDD/PCDF), and occurs mainly in cereal straw and hay, which is given by the use of fertilizers in agriculture. In biomass, so-called inorganic trace elements affecting indirectly the combustion process, pollutant formation, creation of deposits, and others are contained too. These elements are lead (Pb), potassium (K), sodium (Na), calcium (Ca), silicon (Si), etc. [6]. When burning fossil fuels as well as biomass, emissions are released into the air. The average production of ash from wood biomass combustion is approx. 0.4 to 0.7% by weight of burnt wood and approx. 1.5–3% by weight of burnt bark. When burning wood with a volume of $1m^3$, 3 to 5 kg of ash are produced. Ash matter in the firebox cannot be sintered below the temperature of 1100°C, and ash in the form of bulk materials can be used as natural fertilizer, because it contains oxides of calcium, potassium, magnesium and phosphorus. Safety of biomass combustion in hot water boilers has a large influence on human health and safety [7].

2. The state of the art

Biomass is mainly known as firewood (logs), sawdust, wood shavings, wood chips, and a product that is made of them for heating purposes in the form of pellets and briquettes. Their efficient combustion requires a modern technology; many of these fuels have a high moisture content. Others, such as sawdust and straw require a different combustion process owing to their properties. A classic stove cannot effectively use a wood gas that is produced by thermal gasification. Modern technologies came with the double chamber combustion of wood resulting in increased combustion efficiency (i.e. lower fuel consumption) and especially in a high level of output controllability while maintaining rated efficiency [8].

With the problems of domestic and local boilers mainly companies manufacturing their products only in their countries (some only in their surroundings) tackle. So each company develops its own facilities, which are very similar to those of competitors; each of them having its own know-how. Current research in these facilities focuses on the efficiency of the combustion process, which ranges from 80% to 90% [9]. A gasification system is very economical; it delivers fuel savings of up to 40%. This method is introduced as another alternative to innovation. The determination of system performance and concentration of emissions from gasification boilers has been so far provided only by specialized services at the request of manufacturers and users. The measurement itself is laborious, time consuming, and therefore relatively expensive. It requires the use of special and expensive aids and measuring instruments [10].

3. The experimental procedure

A hot water boiler of the type MA23 for lump wood gasification with the output of 23 kW (Fig. 1) was subject to output, emissions and safety testing. The boiler is equipped with its own electronic temperature controller and a temperature safety fuse. The boiler status and its equipment were tested in accordance with current technical documentation supplied by the manufacturer. Spruce wood with a moisture content of 20% and a calorific value of 15.266 $MJ \cdot kg^{-1}$ was used for experimental purposes. Air temperature in a test room as well as temperature of air being sucked into the combustion chamber was 22.15°C on an average. An exhaust throat of the hot water boiler with a diameter of 150 mm was connected to a section for gas measurement and associated with a chimney of 6 m height and 300 mm diameter. When determining the heat output, boiler efficiency, combustion time, components in the combustion gas and exit-flue gas temperature, the boiler was operated at the heat output in its output range throughout testing. All tests of the hot water boilers were conducted at the Faculty of Mechanical Engineering in Žilina (Department of Power Engineering) having necessary modern and testing equipment. The thermal efficiency of the hot water boiler tested was evaluated by a direct method. The test of hot water boilers consists of tests to determine the capacity, including an operational safety test for combustion equipment verifying the thermal overload resistance of the boiler. To evaluation parameters of the tests belong the efficiency, emission conversion, functionality test of the surplus heat removing equipment. There is a requirement for low-emission combustion in boilers operated even at low heat output capacity, which shall not be less than 40% of the rated heat output capacity. The hot water boiler being under test is placed on a weighing machine owing to the measurement of fuel consumption. A throat for the evacuation of combustion gases is connected to an isolated section for flue gas measurement with measuring points for measuring the flue gas temperature (chimney temperature), chimney draught, flue gas composition (carbon dioxide, oxygen, carbon monoxide, nitrogen monoxide and also NO_x), and for taking the samples of the unburnt solid particles. To keep the draught constant, an exhaust fan for venting is placed there. Its speed is regulated by a frequency converter. The flue gas temperature is measured by a temperature sensor located inside a probe sucking the flue gas. The probe has three sampling points; one of them is placed in the middle of the smoke-flue duct. The other two are located within one quarter distance of the smoke-flue duct diameter from the edge of the wall. The flue gas composition was measured by a spectral analyzer PHOTON evaluating the concentrations of carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), sulphur dioxide (SO_2) using a technology known as NDIR (nondispersive infrared method). An electrochemical sensor was used to evaluate the oxygen (O_2) and nitrogen dioxide (NO_2) concentrations. The measured concentrations were converted to standard conditions (pressure of 1013.25 Pa, temperature of 273.15 K) and the reference oxygen content (6% for biomass boilers). A mean value of the volume emissions [ppm] is converted to a unit of mass [$mg \cdot m^{-3}$], whereas for calculations were used the following relations: P_{CO} = 1.25 kg (n) m^{-3}, P_{NO2} = 2.05 type Isostack. The content of solids in the flue gas was measured and evaluated by a gravimetric method. The measurement of solids was carried out using apparatuses as given in [11].

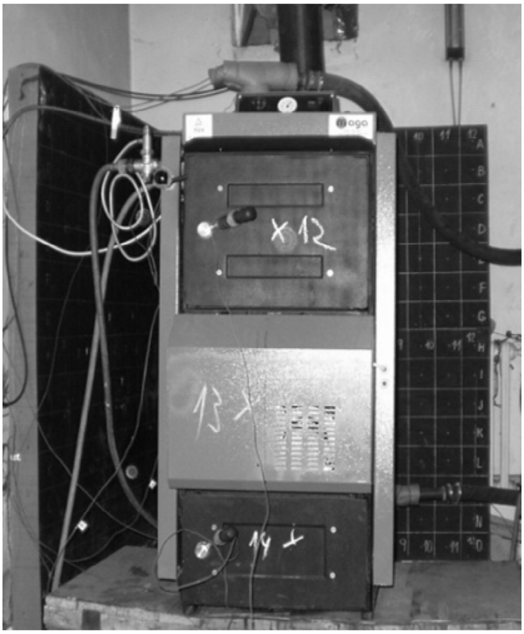

Fig. 1. The hot water boiler MA 23 – test probe connection [14]
Rys. 1. Kocioł MA 23 do wody gorącej – połączenia testowe [14]

Each of the tests lasted 240 minutes; no external intervention, the boiler stoked once. For maintaining the rated output, a standard electronic control unit that was part of the boiler was used. The unit controls the boiler on the basis of measurement of outlet water temperature.

4. The hot water boiler MA23

The hot water boiler MA23 (Fig. 2) belongs to the gasification boilers for combustion of dry lump wood. Owing to its output it is intended primarily for the heating of family houses, cottages, small office buildings and other small buildings. The maximum required heat output is 23 kW. The boiler works on the principle of fuel gasification. The boiler consists of two chambers that are placed one above the other. The upper chamber serves as a fuel hopper with a process of burning away. The lower serves as a combustion chamber and ashtray. This type of boiler can be regulated by the combustion air. The hot water boiler is made of steel. At the bottom of the combustion chamber there is an afterburner chamber, in which a refractory concrete deflector is placed. The combustion air intake is realized by using a radial fan. In addition, combustion in hot water boilers must be safe; emissions will be low, while the minimum heat output capacity will not be greater than 30% of the rated heat output capacity of hot water boilers. The minimum value of the heat output capacity may be higher in hot water boilers with manual fuel feeding. The amount of heat generated should be determined by the manufacturer. This shall be included in documentation.

The boiler provides fuel pre-drying with subsequent gasification at a high temperature. Both the primary and the secondary air flow are preheated and then distributed in a desired, ideal proportion to the boiler firebox and to the nozzle.

The primary combustion air is driven into the combustion chamber through the space beneath the upper door. An even distribution of the preheated primary air ensures that only smaller amounts of fuel are gasified. Therefore, the boiler is highly economical and has a high heating coefficient of performance – 85–89% throughout the output capacity range. This design enables a more efficient gasification of rather large pieces of wood. The secondary air that is driven into the gasification nozzle is preheated to a high temperature. It prevents the flame from being chilled and combustible substances burn well. The lower combustion chamber is equipped with fireproof concrete blocks where the process of burning is completed and all particles that fall down to this space are completely burnt.

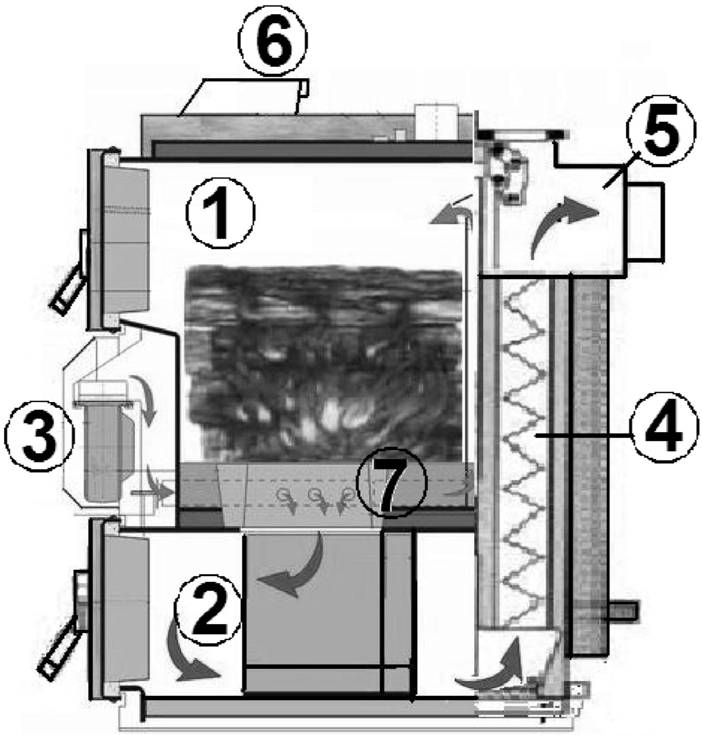

Fig. 2. Hot water boiler MA23, where: 1 – feed chamber, 2 – combustion chamber, 3 – fan, 4 – tube heat exchanger, 5 – chimney neck, 6 – electronic controller, 7 – refractory concrete deflector

Rys. 2. Kocioł MA23 do wody gorącej: 1 – komora zasilania, 2 – komora spalania, 3 – wentylator, 4 – rurowy wymiennik ciepła, 5 – szyjka komina, 6 – sterownik elektroniczny, 7 – żaroodporny deflektor betonowy

5. The results and discussion

Basic measurements were carried out using the direct and the indirect method according to relevant standards and regulations for the Slovak Republic, Czech Republic and European Union. In the whole extent from ignition to extinction with regard to the need to compare modifications of the fitting, we chose for evaluation a range of temperatures of water being heated from 60°C to 90°C, i.e. the working range of temperatures at which the boiler was operated most frequently. We were interested in the measurement of amounts of CO (product of incomfortable combustion), boiler output and temperature of outlet water depending on the temperature of the flue gas. A record of the measured carbon monoxide production for the first experimental measurements of rated heat output of the gasification boiler showed very disappointing results. As can be seen in Fig. 3, the mean value of carbon monoxide (CO) concentration was almost 8000 mg·m^{-3} in the case of boiler stoked with fuel twice.

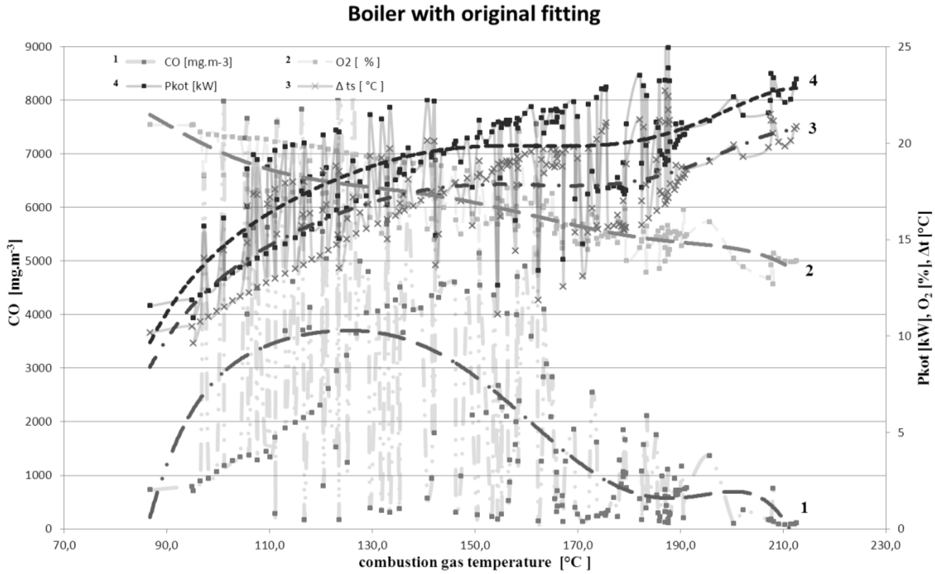

Fig. 3. Data from measurement in a case of the original fitting
Rys. 3. Charakterystyka urządzenia/kotła oryginalnego

The mean value of carbon monoxide concentration in the case of boiler stoked twice (original fiftting, see Fig. 4) without modification of the combustion air distribution was 2.072 mg·m^{-3}.

The gasification boiler had to undergo modification concerning the combustion air and gas intake (Fig. 5) into the secondary combustion zone, see 7 in Fig. 2.

The newly designed fitting (fireproof shaped piece used for air distribution) has orifices along the longer side intended for the intake of secondary combustion air and gas from the combustion chamber. The combustion modification leads to a lower production of the measured flue gas. The change in the fitting is reflected in the measured values of carbon monoxide concentration with an average of 1375.7 mg·m^{-3}. This result was expected and confirmed by measuring.

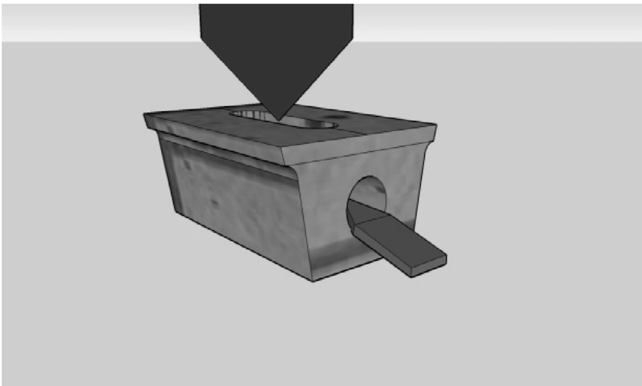

Fig. 4. The original fitting
Rys. 4. Urządzenie oryginalne

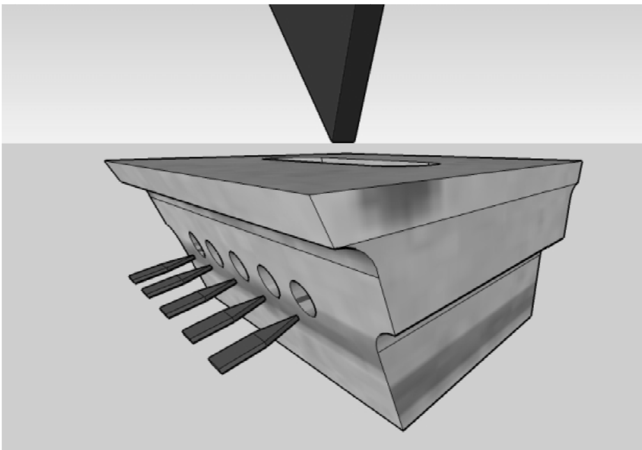

Fig. 5. The new designed fitting
Rys. 5. Nowo zaprojektowane urządzenie

In Fig. 3 data from measurement in a case of the original fitting can be found. Fig. 6 and Fig. 7 show improvement in the combustion process; an improved reaction between the air and the gas being combusted takes place. The first change was a design change. The first two experiments were carried out with the control of air supply depending only on combustion temperature; in the last measurement, with the new fitting and the second stoke, another control member was added to the control computer, namely chimney temperature; another change was that in control electronics.

The mean dispersion is low, which is caused by “jumpy” control of combustion air supply, when fluctuations from the mean value are caused by closing and opening air shutters. In Table 1 the average values of desired quantities are given, and in Table 2 the values of desired quantities at the rated output of the boiler MAGA 23 are presented.

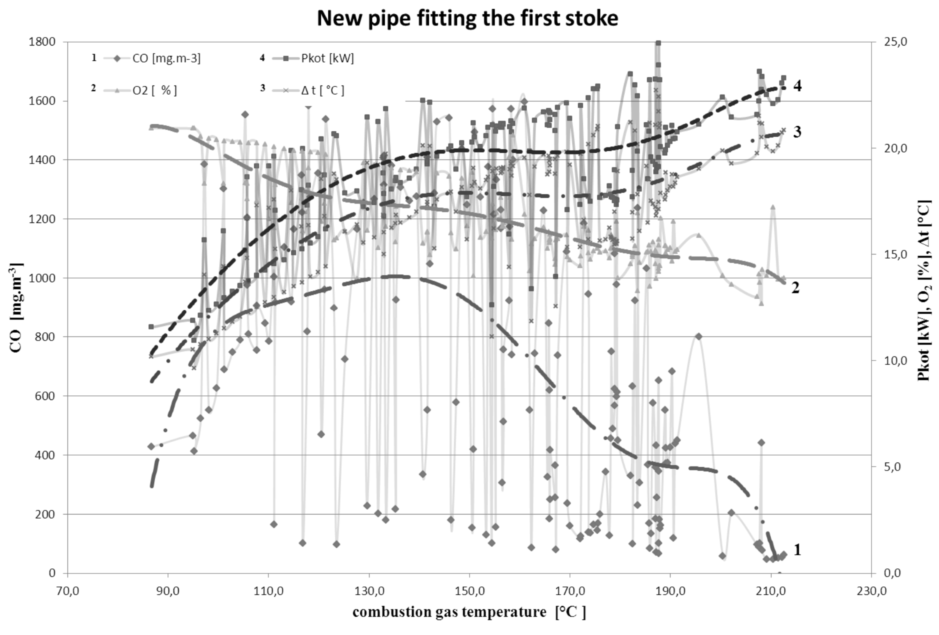

Fig. 6. The new designed fitting: the first stoke

Rys. 6. Charakterystyka nowego urządzenia: pierwsza próba/załadowanie

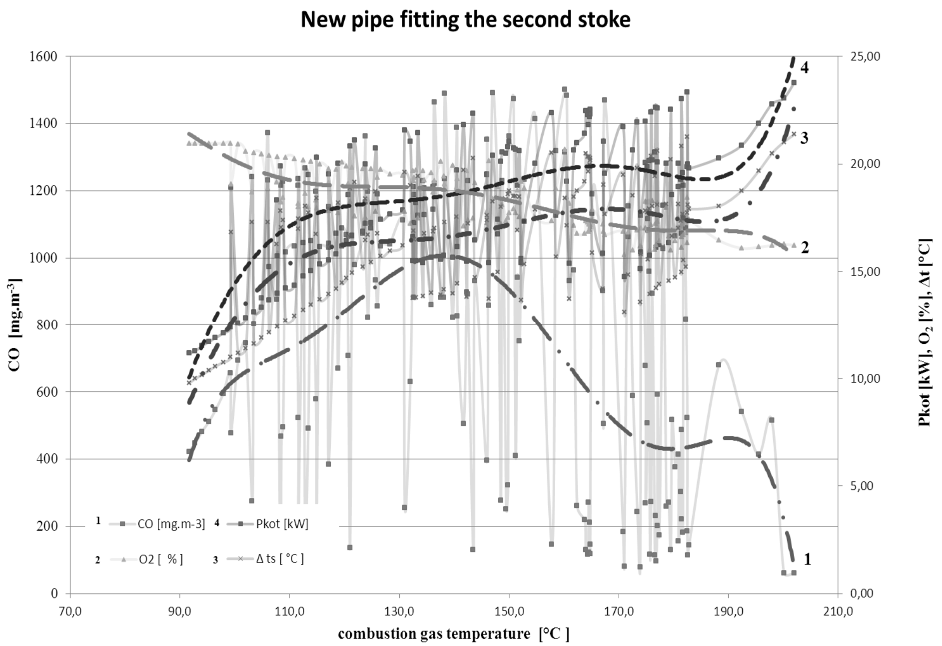

Fig. 7. The new designed fitting: the second stoke
Rys. 7. Charakterystyka nowego urządzenia: druga próba/załadowanie

Table 1. Average values of desired quantities
Tabela 1. Średnie wartości pożądanych/badanych wielkości

	Unit	Original condition	New fitting 1D	New fitting 2D
P_{kot}	kW	19.2	19.3	18.5
CO	$mg \cdot m^{-3}$	2072.0	660.8	696.3
O_2	%	16.6	16.5	18.2
NO_x	$mg \cdot m^{-3}$	115.2	120.4	90.9
Outlet temperature	°C	79.6	79.3	79.4
Chimney temperature	°C	154.3	156.6	145.9
Temperature gradient	°C	17.2	17.3	16.6

Table 2. Values of desired quantities at rated output
Tabela 2. Wartości pożądanych wielkości przy mocy znamionowej

		Original condition	New fitting 1D	New fitting 2D
P_{kot}	kW	23.06	23.06	23.06
CO	$mg\cdot m^{-3}$	92	54	62
O_2	%	13.83	13.8	16.26
NO_x	$mg\cdot m^{-3}$	136.9	244.2	157.5
Outlet temperature	°C	83.5	83.5	88.4
Chimney temperature	°C	212.6	212.2	200.1
Temperature gradient	°C	20.13	20.72	21.02

From the analysis of acquired data, a regression analysis was made to obtain the description and prediction of dependences and relations between individual parameters. From the performed analyses, the following equations (1) to (10) for dependences were received, see Fig. 8.

Chimney draught on output:

$$p_k = 35.78498 + 2.0755 \cdot P_{kot} \quad ; \quad R^2 = 0.97 \tag{1}$$

Chimney temperature on output:

$$t_k = 124.14299 + 3.075308 \cdot P_{kot} \quad ; \quad R^2 = 0.93 \tag{2}$$

Instantaneous oxygen balance factor K_{kb} on p_k:

$$K_{kb} = \frac{1.136 \cdot p_k}{p_{kOPT}} \tag{3}$$

Fan revolutions on output:

$$N_{ot} = 10^{(2.265 + 0.325 \cdot \log(P_{kot}))} \tag{4}$$

Fan revolutions on temperature in chimney exhaust pipe bend:

$$N_{ot} = 10^{(2.265 + 0.325 \cdot \log(-1406.4927 + 49.81042 \cdot t_k - 0.69949 \cdot t_k^2 + 0.00494 \cdot t_k^3 - 1.75068 \cdot 10^{-5} \cdot t_k^4 + 2.49413 \cdot 10^{-8} \cdot t_k^5))} \tag{5}$$

Fan revolutions on chimney draught:

$$N_{ot} = 10^{(2.365 + 0.325 \cdot \log(17.56402 + 0.4526 \cdot p_k))} \tag{6}$$

For values of emissions at $P_{kotOPT} = P_{kotmax} = 23$ kW, the following equations hold true:

$$CO_{prep} = -2912.68649 + 698.44724 \cdot P_{kot} - 55.35295 \cdot P_{kot}^2 + 1.48709 \cdot P_{kot}^3 \quad (7)$$

$$NOx_{prep} = -361.15795 + 79.64852 \cdot P_{kot} - 5.70241 \cdot P_{kot}^2 + 0.14407 \cdot P_{kot}^3 \quad (8)$$

$$CO_{ppm} = -2351.95047 + 578.63494 \cdot P_{kot} - 46.84466 \cdot P_{kot}^2 + 1.27787 \cdot P_{kot}^3 \quad (9)$$

$$CO_{cmg} = -1782.53905 + 438.61597 \cdot P_{kot} - 35.51257 \cdot P_{kot}^2 + 0.96881 \cdot P_{kot}^3 \quad (10)$$

$$NOx_{ppm} = -77.93008 + 17.32183 \cdot P_{kot} - 1.24033 \cdot P_{kot}^2 + 0.03233 \cdot P_{kot}^3 \quad (11)$$

$$NO_{ppm} = 49.76939 - 10.47717 \cdot P_{kot} + 0.47193 \cdot P_{kot}^2 \quad (12)$$

Where:

P_{kot} – the boiler output, t_k – chimney temperature,
P_{kotOPT} – the boiler output optimum,
$P_{kotOmax}$ – the boiler output max, N_{ot} – fan revolutions,
p_k – chimney draught,
K_{kb} – instantaneous oxygen balance factor.

At maximum output $P_{kot} = 23$ kW, from the equations (1) to (6) the following values are acquired for the observed operating parameters $p_k = 12.4475$, $t_k = 210.4638$, $K_{kb} = 1.136$, $N_{ot} = 642$. From the equations (7) to (12), the values of emissions are then as follows: CO_{prep} = 1.9633e+003, NO_{xprep} = 207.0828, CO_{ppm} = 1.7237e+003, CO_{cmg} = 1.3070e+003, NO_{xppm} = 57.6966 and NO_{ppm} = 58.4455.

Thus, in Fig. 8 the distribution of functions and their relation with delimitation of the operating area of the boiler from $P_{kotmin} = 18$ kW to $P_{kotmax} = 23$ kW, i.e. the area determined by the minimum and the maximum boiler output, are given. The theoretical minimum output is confined to the area where the values of chimney draught and oxygen balance are negative.

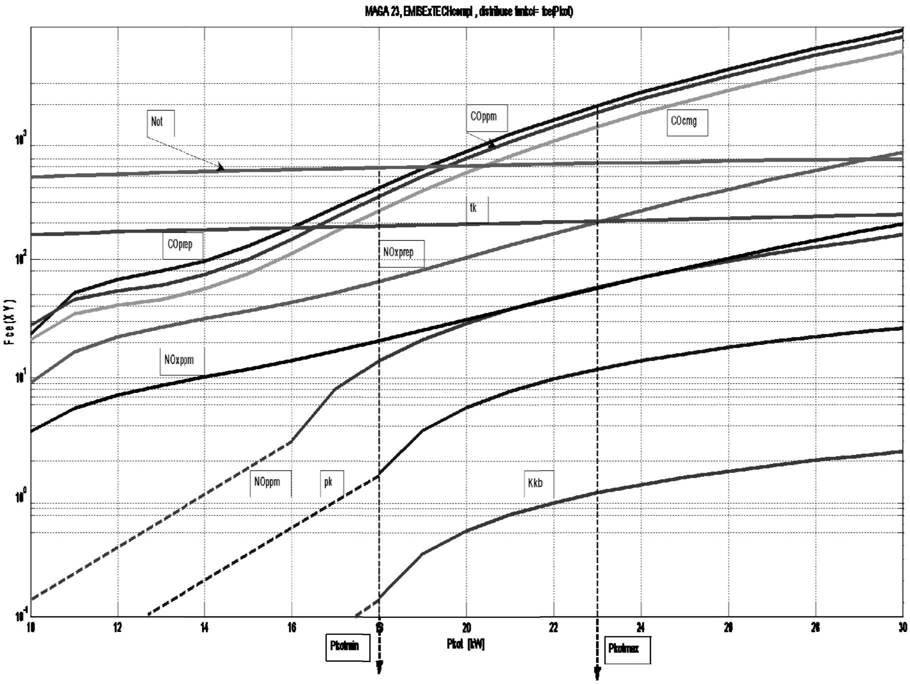

Fig. 8. Distribution of functions and their relation with delimitation of operating area of the boiler from $P_{kot}min$ = 18 kW to $P_{kot}max$ = 23 kW
Rys. 8. Rozkład funkcji oraz ich relacji z rozgraniczenia obszaru roboczego kotła z $P_{kot}min$ = 18 kW do $P_{kot}max$ = 23 kW (pożądanych wielkości mocy znamionowej)

In the graph, instantaneous values of observed operating functions and emissions can be read on the vertical line P_{kotmax} in the case of achieving and permanent maintaining the maximum output of the boiler. The mechanism of combustion process in the boiler can be actively controlled and regulated by boiler fan revolutions according to dependence of the number of revolutions on continuously measured temperature in the chimney exhaust pipe bend (5) by means of e.g. a PID controller. The fan speed can be maintained according to Fig. 9 at 642 rpm. By revolution control, common fluctuations in a very important parameter of combustion, namely the instantaneous draught in the chimney can be simultaneously eliminated according to (6) and Fig. 10.

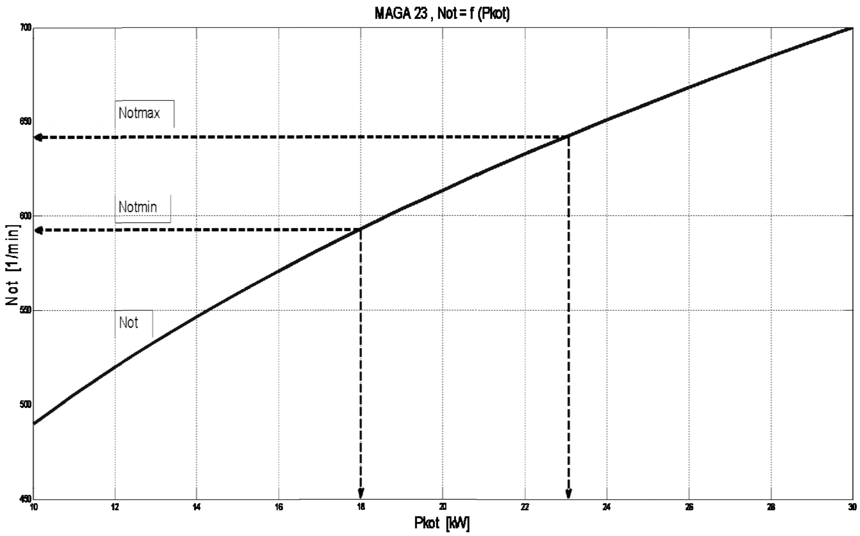

Fig. 9. MAGA 23, N_{ot} = f (P_{kot})
Rys. 9. MAGA 23, N_{ot} = f (Pkot)

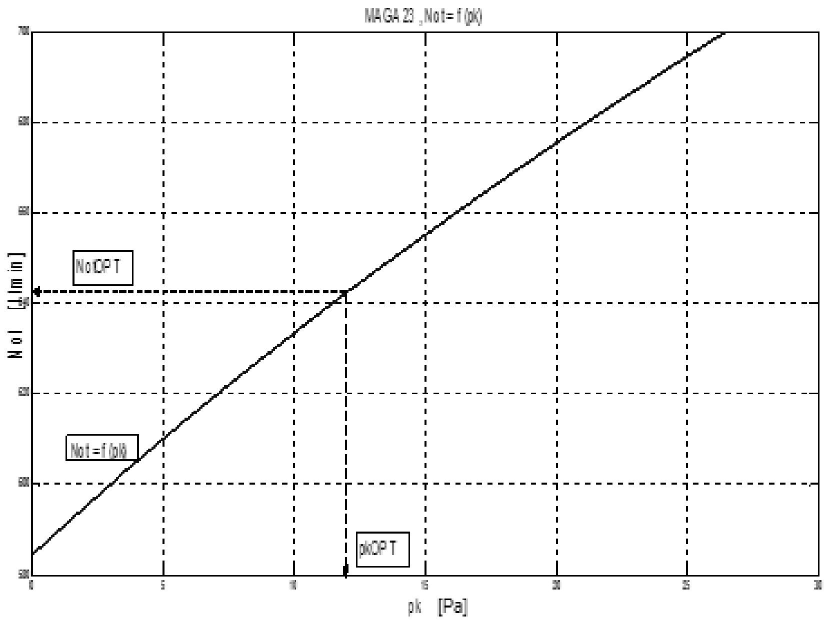

Fig. 10. MAGA 23, N_{ot} = f (p_k)
Rys. 10. MAGA 23, N_{ot} = f (p_k)

6. Conclusion

By the action of high temperatures, flammable gaseous components, a so-called wood gas, are released from dry biomass. If air is present, burning will take place, i.e. simple combustion. If it is a case of heating in the absence of air, the generated wood gas is drawn off to the combustion chamber, where it is combusted like other gaseous fuels. A part of generated heat is used for the gasification of another part of biomass. The advantage is easy output control, low emission and high efficiency.

The replacement of a fitting was carried out to mix better the secondary combustion air as can be seen not only in tables (tables of mean and also rated values, graphs). Gasification is performed so that as great as possible part of energy from the fuel may be transformed to the energy content of the gas. The advantage of gasification in comparison with direct combustion is the better usability of a technology for power generation with higher efficiency and lower emissions. The process of combustion of the produced gas can be controlled better as well.

The aim of this modification was air distribution to more reaction places in the nozzle, when the wood gas is mixed with the combustion air. Thus a reaction takes place between the combustible component CO and the air in the flue gas, and produces CO_2, when this product is regarded in the case of biomass combustion as neutral (according to the definition of biomass).

The reason why the continuity of control cannot be adjusted as easily as in gas boilers is evident; the instantaneous composition of the fuel, i.e. wood gas, is not constant. The composition changes according to the development of gas from lump wood, depends on many variables, such as combustion air supply, reaction area of lump wood, temperature in the chamber, chimney draught, instantaneous value of oxygen balance, etc. As a result of variability in gas composition, i.e. one of the main factors, the control of output is complicated and “jumpy”. Because the control depends on the time when demand for heat supply to the heating system decreases, we must consider this time. This is clear in graphs constructed from the measurements.

So far, the majority of control systems have used for control the temperature gradient of heating water, difference between the temperature of outlet water and that of return water in the heating system. This parameter depends on the temperature in the room, because according to this gradient, the cooling of the boiler changes and thus also the control has several stages. Most frequently, several degrees before achieving the required temperature of the systems, the attenuation of the boiler occurs. This control should be maintained for safety reasons. We would like to include the chimney temperature into control, because this control parameter can be easily measured and is closely connected with variations in the chimney draught. Dependences of individual components of the flue gas can be related to this temperature and instantaneous values then directly regulated by the revolutions of the fan according to the developed equations to the values of optimal combustion.

This assumption is also confirmed by the granted patent and the granted utility model [15], [16]. It was demonstrated by several measurements using not only the given device MA23, but also other types of boilers from the company MAGA Ltd. On the basis of this fact, new developed equations describing the mechanism of combustion in the boiler and enabling the control and regulation of the process, especially by fan speed control are presented in the contribution as well.

For ensuring the constant required chimney draught, the chimney (exhaust) fan is used. It helps the flue gas to pass through heat exchangers and to transfer as much heat as possible to the heating system. The benefit of these modifications is not only an increase in the efficiency of the device in the course of its operation, but also the economic aspects for both the manufacturer and the customer who will buy the boiler. For the manufacturer it means higher sales in the market, because the device will be more economical and environmentally friendly. For the assessment of these parameters, European regulations and special regulations for specific countries and their requirements are issued. According to these regulations, evaluations are carried out and certificates are granted. The design change in the fitting, which decreased a portion of unburnt combustible component of fuel gas, e.g. NO_x, and thus increased the utilization of the fuel and the efficiency of the whole process, was the most important.

Acknowledgements

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Modyfikacje dotyczące powietrza spalania w kotłe pirolitycznym

Streszczenie

Kotły zużywają do 90% energii zawartej w drewnie. Istnieje szeroka gama klasycznych kotłów z ręcznym sterowaniem i bezpośrednim spalaniem drewna oraz nowoczesnych automatycznych kotłów zgazowania dostępnych na dzisiejszym rynku. Wielką zaletą tej nowoczesnej technologii jest możliwość wykorzystania do 90% energii zawartej w drewnie, co skutkuje niższym zużyciem paliwa. Ponadto technologia ta ma znacznie niższy negatywny wpływ na środowisko, zmniejsza ilość niespalonych cząstek stałych w popiele i dlatego

wymaga niewielkiej konserwacji i czyszczenia. Artykuł dotyczy modyfikacji sprzętu spalania niezbędnego do obniżenia emisji z biomasy w kotle typu MA23. Modyfikacja konstrukcji polegała na zmodyfikowaniu wlotów nawiewanego powietrza wtórnego dla umożliwienia połączenia z gazem drzewnym. Wzrost intensywności mieszania gazów i powietrza z gazem drzewnym zmniejszyło stężenie składnika substancji palnej w gazach spalinowych.

Badaniom poddano skład spalin i możliwości wpływania na skład gazów spalinowych i na podstawie doświadczeń zaproponowano sposób modyfikowania i kontrolowania procesu spalania. Tylko jedną z wielu propozycji wybrano do badań. Podczas spalania stanowi ona podstawowy punkt odniesienia w produkcji emisji gazów spalinowych powstających z drewna. Zmodyfikowany sposób montażu sprzętu/kotła został wykorzystany do wtórnej modyfikacji powietrza wlotowego użytego do spalania. Sprzęt został przetestowany zgodnie z normą europejską EN 303-5. Podstawowym wymogiem było ograniczenie emisji, poniżej wymaganych wartości granicznych. W artykule przedstawiono zbiór nowo uzyskanych równań opisujących mechanizm spalania w kotle oraz pokazano jak regulować i kontrolować proces, zwłaszcza regulację prędkości obrotów wentylatora.