THERMAL POWER OF SMALL SCALE MANUALLY FED BOILER

by

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This study reviews test results of the combustion of square soybean straw bales used as fuel in manually fed boiler with nominal thermal power of 120 kW_t. The influence of the mass flow rate (180, 265, 350, 435, and 520 kg/h) of inlet air and flue gas re-circulation (0%, 16.5%, and 33%) fed to the boiler furnace was continuously monitored. Direct method was used for determination of the boiler thermal power. Correlation between boiler thermal power and bale residence time has been observed and simple empirical equation has been derived. General conclusions are as follows: the increase of the flow rate of inlet air passing through the boiler furnace results in decrease of the bale residence time and increase of the boiler thermal power. Share of the flue gas re-circulation of 16.5% increases bale residence time and decreases average boiler thermal power in all regimes except in the regime with inlet air flow rate of 265 kg/h. In regime with 0% flue gas re-circulation boiler thermal power was higher than nominal in regimes with 435 and 520 kg/h inlet air flow rates. In regimes having inlet air mass flow rate of 350 kg/h boiler thermal power is equal to the nominal power of 120 kW_t.

Key words: *boiler, thermal power, soybean straw combustion, inlet air*

Introduction

Biomass exploitation as energy-generating product is not a novelty in Serbia. Agricultural biomass residues have always been used for energy generation in the country's agricultural regions. The most frequently used residues for energy generation are crop residues of cornstalk, wheat, barley, rye, oats, soybean, and rapeseed straw [1]. Biomass is cheap and available fuel, but its utilization is linked to the problems of its collection, form preparations, transportation, and storage [2]. Such biomass is mainly prepared in the form of small and large square or round bales, since it is the cheapest way of agricultural biomass preparation for energy generation [3, 4].

The combustion of baled biomass in Serbia is mostly performed in hot water boilers, the most numerous and widespread of which are the boilers with nominal thermal power ranging from 50 to 120 kW_t, with flat fixed grate for combustion. The said boilers are mainly used in heating systems of residential, production, and commercial buildings, in industry, and, for the

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most part, in rural environment [5], *i. e.* in places with larger space available for biomass storage. There are no accurate data on the number of such boilers used in Serbia due to the fact that, in addition to factory production, a large number of boilers are manufactured by local craftsmen. Based on the general information obtained from the authors' research, it can be assumed that in Serbia there are over 5,000 boilers with over 300 MW_t of installed power using biomass as energy-generating product.

Although more developed countries use boilers of higher energy efficiency, *i. e.* the standards of used equipment and exploited biofuel are much more developed, the improvement of construction and manner of operation of hot water boilers with flat fixed grates and thermal power of up to 120 kW_t is essential for the more extensive use of biomass for energy generation in the territory of Serbia. Widely used constructions of boilers with flat fixed grate rarely exceed thermal power of 500 kW_t , but, regardless of their power and manner of construction, they encounter major problems during operation [6]. Some of the most prominent problems in operation of the said boilers are: significant varying in the intensity of generated thermal power, frequent thermal overload of combustion chamber, sudden cooling of combustion chamber (while inserting new bales of biomass), emission of flue gases with high concentration of uncombusted compounds (CO, H_2, CH_4, *etc.*), which occasionally reach high temperatures (over 650 °C), especially in order to obtain as higher as possible thermal power output of the boiler plant. In addition to the above mentioned problems, a specific problem encountered during the operation of boiler plants for agricultural biomass combustion is also ash melting at relatively low temperatures [5], resulting in clogging of primary air inlet and, consequently, in incomplete biomass combustion or even the impossibility of biomass combustion [7].

Such a large number of bad indicators in boilers operation have as a consequence the reduction of plant exploitation period, significant decrease of energy efficiency of operation, increase of biofuel consumption, and a distinct harmful effect on the environment as a result of the emission of flue gases in harmful concentrations (CO, H_2, CH_4, NO_x, char, *etc.*) [8].

Aware of the fact that boiler plants with flat fixed grate and power of up to 120 kW_t will continue to be used in Serbia for many years from now, researches have been conducted aiming at determining to the largest possible extent the dependency and correlativity of factors important for the combustion process of biomass bales, and reaching conclusions in order to improve the operation of the said plants. Accordingly, the researches from this paper are aimed at defining the correlation between thermal power output and the quantity and composition of air for the combustion of soybean straw bales in hot water boiler plant with flat, fixed, and water-cooled grate.

Obtained results can be used for the improvement of boiler plant operation technology (manner and dynamics of feeding the furnace and adding combustion air), introduction of automation in the operation of such plants, and improvement of their construction solutions.

Boiler plant and measuring points

Examination of the impact of quantity and composition of combustion air on thermal power output has been conducted on a manually fed hot water boiler plant of nominal power of 120 kW_t. The boiler is shown in fig. 1 together with the most important measuring and regulation equipment used for the experiments.

The boiler (Item 3) is box-like, made of boiler tin (without chamotte walls), coated with 50 mm thick thermal insulation. Vertically, the boiler has got four mutually connected functional wholes: ash collector, furnace, secondary combustion chamber (of volatiles) and flue tubes for convective heat transfer between flue combustion products and boiler water shell.

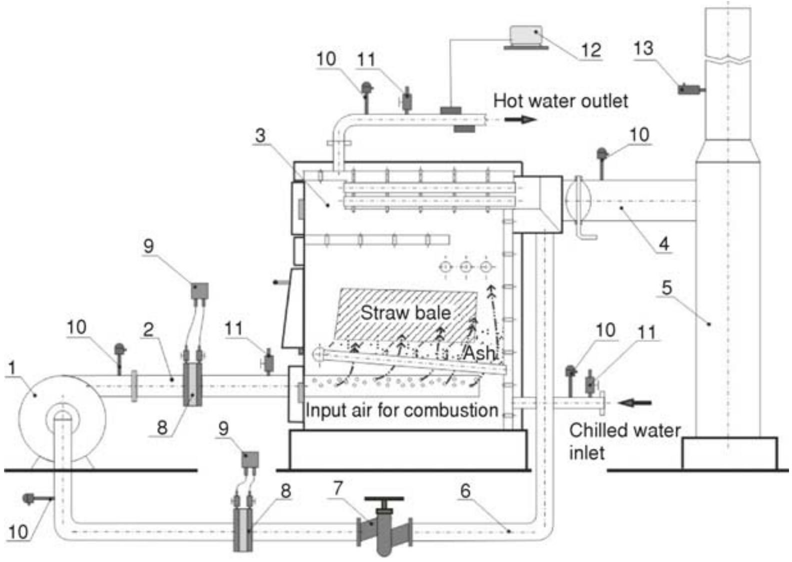

Figure 1. Boiler plant of manufacturer "Ekoprodukt" from Novi Sad with the measuring and regulation equipment
1– centrifugal fan, 2 – combustion air tube, 3 – hot water boiler, 4 – smokestack, 5 – stack, 6 – flue gas re-circulation tube, 7 – flue gas re-circulation valve, 8 – standard orifice flow meter, 9 – differential pressure transmitters, 10 – probe for temperature measurement, 11 – sensor for pressure measurement, 12 – ultrasonic water flowmeter, 13 – flue gas analyzer

There is a perforated tube in the ash collector (Item 2) for combustion air supply into the furnace in the conditions of overpressure by a centrifugal fan (Item 1). The dimensions of the furnace are $600 \times 800 \times 1100$ mm. Biomass is combusted on a flat, fixed, and water-cooled grate made of 60.3 mm tubes spread over the entire cross-section of the furnace. The upper arch of the furnace is surrounded by water shell, and in the rear section under the inlet for flue gases into the volatile secondary combustion chamber there are three water-running tubes set crosswise. These tubes are set in order to strenghten the boiler's construction and enhance mixing of flue gases with the remaining air, *i. e*. oxygen. Flame is developed and high temperatures are achieved in the secondary combustion chamber; accordingly, the combusted straw ash is not exposed to those high temperatures, thus diminishing the danger of its melting. In circumstances of bigger workload, flame front enters approximately 1/5 of flue tubes, cleaning them thoroughly of the ash. Gas combustion products enter the flue tubes from the front diversion chamber, and it is in the tubes that the convective heat transfer between flue gases and water shell takes place. Leaving the flue tubes, flue gas passes into the collection chamber which ends with an exhaust tube for re-circulation of flue gases. After that, flue gas passes through the smokestack and via the stack go into the atmosphere.

Flue gas re-circulation is performed through the flue gas tube (Item 6), valve for the regulation of re-circulation volume (Item 7), and orifice flow meter for measuring the flow of re-circulated flue gases (Item 8). Flue gas tube (Item 6) ends at the entrance to the combustion air fan (Item 1), leaving enough space for the admission of the surrounding fresh air.

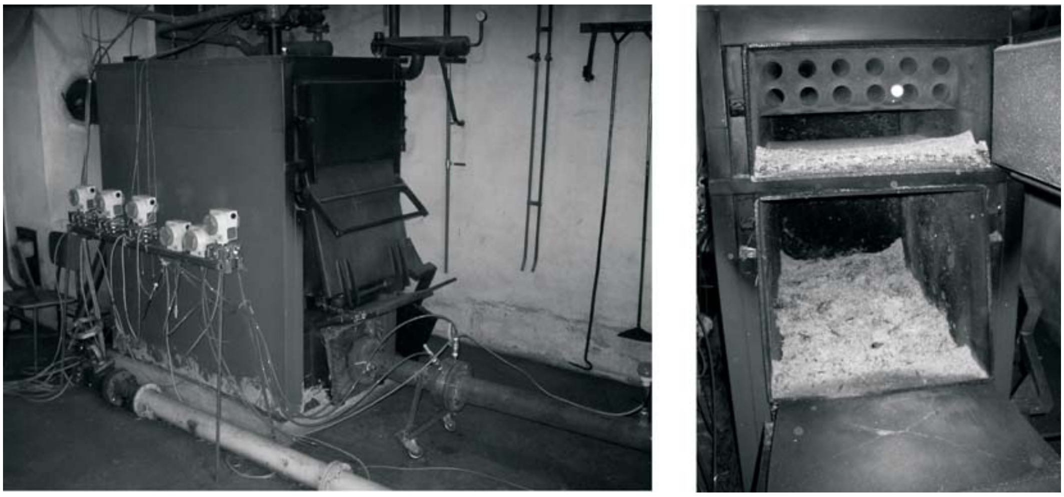

Figure 2. The hot water boiler at the time of research with functional parts: ash collector, furnace, secondary combustion chamber, and the flue gas tube

On the front side of the boiler there are doors to the ash collector, furnace, and secondary combustion chamber (fig. 2). Cooled water enters through the rear water shell of boiler, passes through the grate, via lateral and rear channels, and goes out heated on the upper front part of the boiler.

Boiler exploitation is based on manual feeding with the small square bales of biomass or some other fuel, at the frequency which would provide the desired temperature in the heating system.

The boiler is manually fed, which causes a number of negative effects such as: uneven combustion, variable quantity of air required for combustion of air excess, uneven generation of thermal power, extremely disbalanced composition of flue gases with higher concentrations of char, CO, and other uncombusted products, *etc*.

Due to the aforementioned, and with the aim of eliminating many factors that could potentially lead to wrong conclusions, the experiments in these researches have been conducted in separate regimes in which many influential factors have been eliminated or maintained at a steady level.

For the purpose of determining the impact of the quantity and concentration of combustion air on generated thermal power of the boiler plant, the following measurements, among others, have been performed: flow, temperature, and pressure of combustion air, temperature of outgoing flue gases and their concentration, flow and temperature of re-circulated flue gases, as well as the flow, temperature, and pressure of the incoming and outgoing water of the heating system. Places for the installation of measurement probes are shown in fig. 1.

Materials and methods

Soybean straw characteristics

The material chosen for this work were small square soybean straw bales. The use of soybean straw as biofuel in Serbia is quite significant, since soybeans are grown on the land of over 130,000 hectares of surface area. The form of small square straw bales was chosen because they could be directly inserted into the intended type of experimental plant.

Straw was baled immediately after the harvest, and 250 bales of the same dimensions and mass, and, accordingly, the same density [9], were chosen. They were stored in a storage barn near the boiler plant, so that they were not exposed to additional climate effects, which helped in preserving their quality and prevented their content, shape, and compactness from deterioration.

From a physical and chemical point of view, soybean straw fulfils the majority of requirements for its use as biofuel. Since the soybean straw bales were collected from the same field, and the soil of similar characteristics, where one and the same kind of soybeans had been grown using identical agrotechnical measures (fertilization quota, chemical treatment, *etc*.), it was deemed that representative parameters of proximate and ultimate analysis of soybean straw used for the experiments could be derived by using four samples. Average values of the chosen parameters are presented in tab. 1.

Table 1.Characteristics of soybean as a fuel

Component		Unit	Value
Information on straw bales	Bale dimensions	m	0.35 × 0.5 × 0.8
	Bale mass	kg	11
	Bale density	kg/m	78.57
Proximate chemical analysis	Carbon	%	42.32
	Hydrogen	%	5.57
	Sulphur	%	0.17
	Nitrogen	%	0.34
	Oxygen	%	37.24
	Chlorine	%	0.76
	Ash	%	4.1
	Moisture	%	9.5
Ultimate analysis	Upper heating value	kJ/kg	15.757
	Lower heating value	kJ/kg	14.029
	Volatile matters	%	71.73

The mentioned parameters have been determined at the Laboratory for Thermotechnics and Process Engineering at the Faculty of Agriculture in Novi Sad, Laboratory of Scientific Institute for Field and Vegetable Crops from Novi Sad, and the Laboratory of the Panonian Thermal Power Plants – Thermal Power Plant Novi Sad.

Research method

The applied research method is based on the scientific method of mathematical and statistical analysis on the basis of which it is possible to determine the influence of quantity and composition of combustion air on the process of combustion of small square soybean straw bales (using dispersion analysis), analytical form of those influences (using regression analysis), and the importance of those influences on the observed process (using correlation and determination coefficients) [10].

The main goal of the research was to confirm that mass flow, composition of inlet primary air and degree of re-circulation, are very important factors influencing the combustion process of soybean straw bales, *i. e.* generated thermal power. Other factors having influence on the combustion process were maintained at a steady level.

The chosen research method was aimed at approaching real exploitation processes of combustion in order for the obtained results to have wider practical application.

Being aware of the limited choice of factors and range within which they could be analyzed, it was decided that the change of mass flow rate of combustion air should be observed on 5 levels (180, 265, 350, 435, and 520 kg/h), whereas the level of flue gas re-circulation should be observed on 3 levels (0, 16.5, and 33%). Percentage share of flue gases refer to the total volume of combustion air (mixture of surrounding air and re-circulated flue gases).

In accordance with the plan of research, the experiments were repeated at least three times. After the insertion of a new bale of straw, the system for automatic data collection from the installed probes was activated. Every 5 seconds all data were being recorded. Only the gas analyzer was activated 30 seconds after the commencement of straw bales combustion, due to the fact that, at the beginning of bale combustion, the concentration of CO was always extremely high and it blocked the operation of the gas analyzer. Collected data were displayed in the form of a diagram, and in case of major deviations the experiments were repeated for a larger number of times until obtaining such results the average values of which were further used for dispersion and regression analyses.

Although the boiler was continuously stoked, the experiments in which bales were combusted were performed separately. That was necessary in order to try and maintain at a steady level the quantity and glowing intensity, as one of the most influential factors for combustion dynamics. In addition, separate performance of experiments provided for the adequate definition of values of initial air excess. Besides, the monitoring of combustion process of one bale enabled monitoring of decrease of boiler's generated thermal power down to the relevant values limited by the values of oxygen in combustion products, *i. e.* by the maximal set air excess. The assumption is that the similar uncombusted mass of the bale was left in the furnace at that time. By overlapping of the obtained diagrams it is possible to determine the optimal frequency of bale stoking in different work regimes of boiler plants and operation at lower air excess, which will increase the plant efficiency.

Measuring methods are in accordance with SRPS EN 303-5:2007 standards and DIN 4702 for boiler thermal power determination. Boiler thermal power was determined using a direct method [11], *i. e.* by measuring mass flow of water supply and water temperature at boiler entrance and exit points. More details such as measuring data, bale dimensions, instrument names, measuring ratio, *etc.* can be found in [9, 12]. During the experiments, boiler thermal power was determined based on eq. (1) [14]:

$$P = \dot{m}_{\mathrm{w}} c_p (t_{\mathrm{ow}} - t_{\mathrm{iw}}) \tag{1}$$

where P [$\mathrm{kW_t}$] is the boiler thermal power, $\dot{m}_{\mathrm{w}}$ [$\mathrm{kgh^{-1}}$] – the mass flow of water through the boiler, c_p [$\mathrm{kJkg^{-1}K^{-1}}$] – the specific heat of water, t_{ow} [K] – the boiler outgoing water temperature, and t_{iw} [K] – the boiler incoming water temperature.

Although flue gas re-circulation was not planned for the initial construction of the boiler plant, in addition to regular operation, in the course of its work it was tried to observe the operation of the boiler plant in conditions when, together with the combustion air, re-circulated flue gases were admitted in. Such manner of operation is interesting from many points of view such as: preheating of combustion air, decrease of combustion temperature, reduction of NO_x emission, but the primary hypothesis for examination was that the outgoing thermal power of the boiler plant and its efficiency could be affected by the admission of re-circulated flue gases.

Statistical analysis

Experimental data have been processed using non-linear regression analysis (software packages Mathematica 6 and Statistica 10 were used [12, 13]. The compatibility of analytical formulation for presenting measured data is examined using the following tests: (1) *t*-test examines of the regression coefficients; (2) examination of the significance level of dependable variables, shown by the determination coefficient R^2 for the chosen independent variables and the compatibility of the regression line to the results [15].

This paper presents the analytical approach and expression for correlation between boiler thermal power and bale residence time, for all regimes tested and all values of flue gas recirculation ratios (0%, 16.5%, and 33%). The analysis was performed using the average values of experiments performed in triplicate and at different times for each regime tested.

Results and discussion

The average combustion time of the bales, as well as the average values of boiler thermal power during the whole combustion process are presented in tab. 2. Standard statistical error range of average boiler thermal power is presented as well.

Table 2. Values of the measured bale combustion time and average boiler thermal power

	Degree of re-circulation	Boiler operating regime [kgh^{-1}]				
		180	265	350	435	520
Average combustion time of the bale [s] with standard error [%]	0%	1258	713	670	453	400
	16.0%	1335	642	763	532	427
	33%	943	667	587	480	348
Average boiler thermal power [kW$_t$] with standard error range [%]	0%	75.66	92.24	113.12	96.63	112.94
	16.0%	69.33	85.06	88.98	97.72	111.21
	33%	72.32	77.48	95.01	97.49	114.94

General conclusions are: (1) due to the increase of inlet air flow rate to the boiler furnace, bale residence time decreases and boiler thermal power increases, (2) for all regimes (except for the regime of 265 kg/h), flue gas re-circulation of 16.5% results in longer bale residence time and lower average boiler thermal power, (3) at re-circulation ratio of 0%, average boiler thermal power is the highest in regime of 350 kg/h, (4) comparing re-circulation of 16.5 and 33%, it can be seen that the latter provides higher boiler thermal power, but it is almost certain that this is achieved by the reduced energy efficiency.

Admission of flue gas re-circulation not only reduces nitrogen oxides emission (although this is partially achieved), it also prolongs bale combustion time, and affects boiler thermal power (and energy efficiency). As it can be seen from (tab. 2), these effects are only partly achieved.

Boiler thermal power - experimental data and analytical approach

First task was to express boiler thermal power as a function of air flow rate and bale residence time. According to fig. 3, for higher air flow (435 and 520 kg/h) experimental data should be approximated by exponential function $\exp[-(x-a)^2]$ which is symmetric with respect

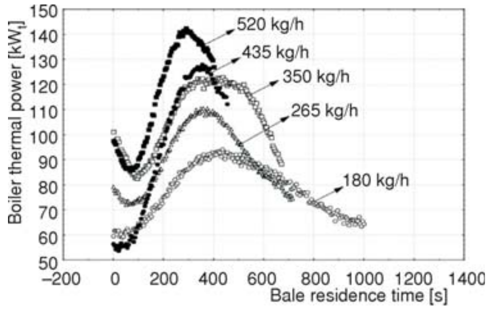

Figure 3. Correlation between boiler thermal power and bale residence time, experimental data, re-circulation 0%

to line $x = a$ and its graphical interpretation corresponds to normal distribution (parameter a is time when maximum thermal power is achieved). Also, according to fig. 3: (a) higher mass of air flow rate $\dot{m}$ implies higher maximum boiler thermal power P (so the function $\exp[-(x - a)^2]$ should be multiplied by air flow rate $\dot{m}$ and regression coefficient b to obtain $b\dot{m}\exp[-(x - a)^2]$; (b) in addition, higher mass air flow $\dot{m}$ makes total combustion time τ_{kr} shorter and graph becomes narrower. Finally, it is proposed that the function $b\dot{m}\exp\{-[c(x - a)/\tau_{kr}]^2\}$ can properly approximate experimental data in regimes with larger mass air flow rate. Regression coefficients a, b, and c are useful for graph corrections according to experimental data. For smaller mass air flow rates (265 and 350 kg/h), experimental data can be approximated by function $\dot{m}\sin[(x - b)/\tau_{kr})$, using the same arguments. Finally, according to the detailed analysis given in [10], analytical form of the empirical correlation between boiler thermal power and bale residence time for different operating regimes can be formulated as:

$$P(\tau, \tau_{kr}\dot{m}) = b_1 + b_2\dot{m}\exp\left[-\left(b_3\frac{\tau - b_4}{\tau_{kr}}\right)^2\right] + b_5\sin\left(b_6\frac{\tau - b_7}{\tau_{kr}}\right) \tag{2}$$

here, b_1, b_2,..., b_7 are regression coefficients given in tabs. 3, 4, and 5, τ – the bale residence time, P [kW$_t$] – the boiler thermal power, $\dot{m}$ [kgh^{-1}] – the mass air flow rate, and τ_{kr} [s] – the total bale combustion time.

If the re-circulation is 0 and 16.5%, in the regimes of 265 and 350 kg/h, bale combustion is slower, while the total bale combustion time is 50% to 100% longer than in regimes of 435 and 520 kg/h. This enables considering regimes of 265 and 350 kg/h together with high air

Table 3. Estimation of empirical regression coefficients and analysis of variance of eq. (2), no re-circulation

Confidence level: 95%, Determination coefficient: R^2 = 90.58%			
	Estimate	*t*-test	Confidence interval
b_1^*	44.7503	54.55	(43.139, 46.362)
b_2^*	0.3392	58.09	(0.328, 0.351)
b_3^*	–2.3073	–57.02	(–2.387, –2.228)
b_4^*	264.8410	60.81	(256.286, 273.394)
b_5^*	0.1272	34.11	(0.120, 0.135)
b_6^*	3.7176	40.96	(3.539, 3.896)
b_7^*	411.0314	45.24	(393.190, 428.873)

* Significant coefficients at significance level of $P < 0.05$

Table 4. Estimation of empirical regression coefficients and analysis of variance of eq. (2), re-circulation 16.5%

Confidence level: 95%, Determination coefficient: R^2 = 89.02%			
	Estimate	*t*-test	Confidence interval
b_1^*	46.4998	59.85	(44.975, 48.025)
b_2^*	0.2664	55.42	(0.257, 0.276)
b_3^*	2.2642	33.64	(2.132, 2.396)
b_4^*	369.1090	104.89	(362.200, 376.018)
b_5^*	0.0771	27.23	(0.0715, 0.0826)
b_6^*	3.5358	21.51	(3.2130, 3.8586)
b_7^*	624.9482	43.40	(596.678, 653.219)

* Significant coefficients at significance level of $P < 0.05$

flow rate regimes using empirical correlation (2). Re-circulation of the flue gas of 33% makes bale combustion faster, but injection of the excessive amounts of air deranges bale combustion, as it has been confirmed in a couple of independent studies [12, 16], and those regimes cannot be considered using correlation (2).

Experimental data and empirical correlation (2) of the boiler thermal power *vs*. bale resistance time are presented in figs. 3 and 4, for regimes with 0% re-circulation). If there is no re-circulation of flue gases into the furnace, then three operating regimes can be regarded as optimal (265, 350, and 435 kg/h) with reference to boiler thermal power values and time necessary for the total bale combustion. In the operating regime of 265 kg/h, the maximum boiler thermal power was 108.12 kW_t with $\tau_{kr} = 713$ s. In the operating regime of 350 kg/h, the maximum boiler thermal power was 120.02 kW_t and $\tau_{kr} = 670$ s, and in the regime of 435 kg/h the maximum boiler thermal power was 126.42 kW_t and $\tau_{kr} = 573$ s. Increase of the intake air flow rate increases maximal thermal power and at the same time decreases bale residence time.

Experimental data and empirical correlation (2) for two other re-circulation values can be seen in fig. 5, 6, 7 and 8. If the flue gas re-circulation of 16.5% (or 33%) is used, total bale combustion time is longer, but average thermal boiler power is lower compared to regimes with zero re-circulation (tab. 6).

Table 5. Estimation of empirical regression coefficients and analysis of variance of eq. (2), re-circulation 33%

Confidence level: 95%, Determination coefficient: $R^2 = 88.75\%$			
	Estimate	*t*-test	Confidence interval
b_1^*	47.2398	60.33	(45.701, 48.778)
b_2^*	–0.0575	–14.68	(–0.0652, –0.050)
b_3^*	–4.0827	–12.62	(–4.718, –3.447)
b_4^*	179.1803	33.65	(168.718, 189.643)
b_5^*	0.2129	43.29	(0.203, 0.223)
b_6^*	2.0180	50.60	(1.940, 2.096)
b_7^*	–77.9528	–12.62	(–90.084, –65.822)

* significant coefficients at significance level of $P < 0.05$

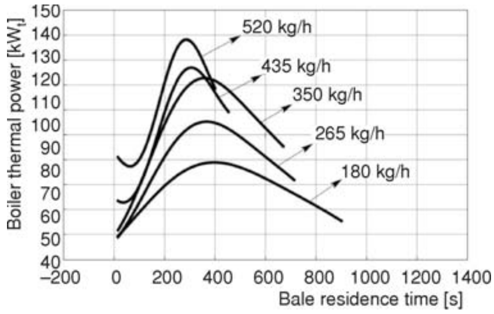

Figure 4. Correlation between boiler thermal power and bale residence time, model (1), re-circulation 0%

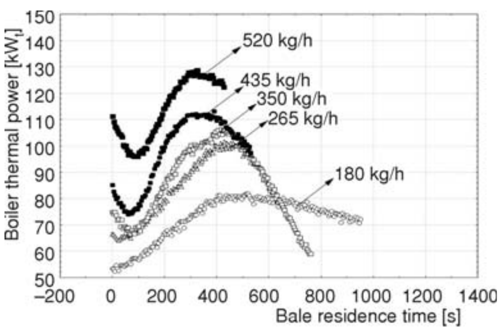

Figure 5. Correlation between boiler thermal power and bale residence time, experimental data, re-circulation 16.5%

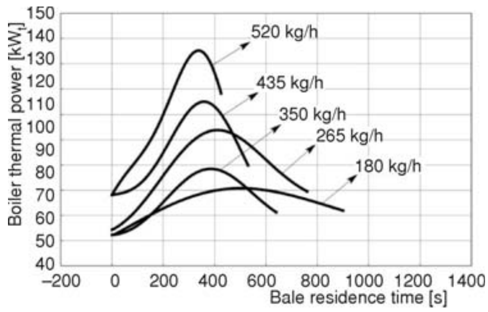

Figure 6. Correlation between boiler thermal power and bale residence time, model (1), re-circulation 16.5%

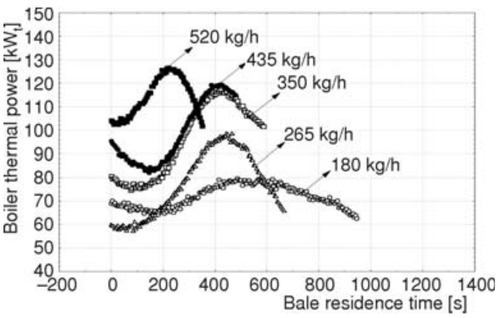

Figure 7. Correlation between boiler thermal power and bale residence time, experimental data, re-circulation 33%

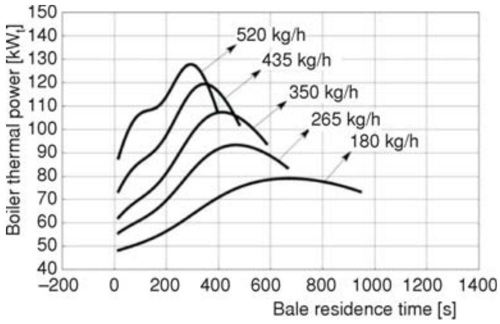

Figure 8. Correlation between boiler thermal power and bale residence time, model (1), re-circulation 33%

Maximum boiler thermal power and energy efficiency

To determine compliance between analyzed regimes and nominal boiler power, it is necessary to find out at what time, starting from the moment of bale feeding, the maximum boiler thermal power is attained. Maximum boiler thermal power and corresponding time necessary in order to achieve maximum thermal power are presented in tab. 6 for all regimes that have been examined.

The boiler attains maximum power in the first half of the time period necessary for total combustion of the straw bale. In regimes with air flow rates of 180 and 265 kg/h and with zero re-circulation, maximum power is smaller than nominal (120 kW for 350 kg/h). In regime with 350 kg/h air flow rate, maximum thermal power of boiler is identical with nominal power of 120 kW$_t$. In regime of 435 and 520 kg/h, maximum boiler thermal power is higher than nominal. It follows that those regimes are not suitable for this specific boiler design, since thermal power higher than nominal can cause damage to the exploited boiler.

Table 6. Time of reaching the maximum thermal power

	Degree of re-circulation	Boiler operating regime [kgh^{-1}]				
		180	265	350	435	520
Time necessary to reach maximum thermal power τ [s]	0%	435	415	520	385	325
	16.5%	880	630	485	505	375
	33%	840	465	505	465	275
Maximum thermal power P_{max} [kW$_t$]	0%	94.05	108.12	120.02	126.42	138.61
	16.5%	74.57	78.55	103.24	101.91	127.01
	33%	71.66	98.56	110.49	116.28	122.56
Maximum energy efficiency η_{max} [%]	0%	84.49	51.13	54.17	39.38	41.90
	16.5%	78.75	56.12	53.30	43.75	39.67
	33%	54.74	39.14	42.60	38.23	34.05

In regimes with low air flow rates, implementation of re-circulation creates significantly worse conditions for combustion of straw bales, leading to decrease of boiler thermal power. Re-circulation of 16.5%, for high air flow rates has positive impact on the conditions of straw combustion, due to preheating of inlet air. Favourable combustion conditions enable higher maximum boiler thermal power and higher boiler efficiency compared to the case when there is no re-circulation. Extremely high re-circulation of 33% did not provide positive results as it was expected. For this degree of re-circulation better parameters of bale combustion are obtained at higher air flow as well. It is most probable that such results can be explained by the positive influence of air preheating on combustion of soybean straw bales. Generally, it can be concluded that re-circulation of 33% is not adequate and should be avoided. Using higher air flow regimes is desirable when re-circulation is 16.5%.

The degree of boiler efficiency in work regimes ranged from 34% to 84.49%, and as a general conclusion it could be noted that when achieving nominal rated power of the boiler of 120 kW_t, in regimes of re-circulation of 0%, 16.5%, and 33%, boiler efficiency degrees of 54.2%, 43.5%, and 35%, respectively, were attained.

Conclusions

The results obtained by detailed testing of the boiler in real exploitation circumstances, and as such presented in the paper, show that the optimal operating regimes are obtained when the air flow rate through the furnace reaches 265 and 350 kg/h, with zero re-circulation. Re-circulation of 33% caused the characteristics of the boiler to deteriorate.

Average boiler thermal power ranges between 75.66 kW_t and 113.12 kW_t if there is no flue gas re-circulation. Boiler thermal power ranges between 69.33 kW_t and 111.21 kW_t with 16.5% re-circulation, and from 72.32 kW_t to 114.94 kW_t with 33% re-circulation.

The presented empirical correlation can be considered as valid for the given boiler and the conditions under which the experiment was conducted. The applied analytical approach and obtained empirical correlation can be used for different engineering purposes. Apart from giving the basic information on soybean straw bale combustion that can be used to obtain higher boiler thermal power and plant energy efficiency in real operating conditions, results can be applied for the design of future plants, as well as for the reconstruction and automation of the existing power plants.

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