EXPERIMENTAL STUDIES OF WOOD CHIPS CHARACTRISTICS INFLUENCE ON BOILER PERFORMANCE AND POLLUTANT EMISSIONS

by

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Wood chips are often used as solid fuel in modern biomass boilers. Experiments were conducted on 22 boilers located in Serbia burning wood chips as fuel. The influence of wood chips characteristics is analyzed in relation to the flue gas losses and the thermal efficiency of the boiler. Measured useful heat output of the tested boilers was 460-2585 kW. Moisture content of the wood chips was 19.21-38.23% with a net calorific value of 10177-14139 kJ/kg and ash content of 0.84-3.59%. Thermal efficiency of the boilers was 88.78-94.06%, flue gas losses 5.84-11.13% and flue gas temperature 121.83-188.44 °C. Experimental research and analysis of the results showed that an increase in moisture content of wood chips lead to a decrease of net calorific value i.e., decrease in flue gas temperature. Moisture content of wood chips has an influence on both useful heat output and boiler thermal efficiency. The experimental results showed that for a given boiler construction, this impact is not negative. Based on regression analysis, mathematical expressions were derived for the calculation of thermal efficiency and flue gas losses. Throughout the experiments, pollutant emissions were measured, NO_x, CO, and particulate matter.

Key words: *boiler, wood chips, moisture content, flue gas losses, thermal efficiency, regression and correlation analysis*

Introduction

There has been an evident increase in air pollution in recent years. The dominant sources of air pollution in urban and rural areas during the heating season, are small individual appliances. With respect for biomass potential [1], in recent years, new combustion plants have been built in several locations in Serbia, which use biomass as fuel – wood chips. These plants were built in order to replace multiple existing low-rank coal combustion plants, combining them into one combustion plant. Experimental studies concerning both performance and emissions of biomass boilers were carried out and are described in [2-7].

Thermal efficiency of boiler burning wood biomass depends on the construction of the combustion chamber of the boiler and the properties of the wood biomass. Especially when the fuel is wood chips moisture content of the fuel varies widely. The problem with such fuel is to maintain the combustion process within acceptable environmental and economic limits [8].

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Quality and moisture content in wood chips significantly affect its energy properties. Therefore, many studies consider the effect of moisture on thermal efficiency and boiler operation. One way to reduce heterogeneity and to guarantee wood chips qualities defined in accordance with relevant ISO 17225-4 standard is the pretreatment of wood chips [9, 10].

Bošnjaković *et al.* [8] consider the influence of moisture on pollutant emission and the degree of boiler operation during actual operating conditions of a 5 [MW] cogeneration plant. They concluded that moisture content has a significant impact on the heating value of wood chips, thermal efficiency of the boiler and emissions of the CO.

Swithenbank *et al.* [11] reviews innovative combustion system options and the technical factors of burning wood as a fuel in today's developing solid fuel market *i.e.* wood chips. The [12] also evaluates boiler efficiency briquettes made using different techniques. Maintaining control over the combustion process optimizes the combustion process, minimizing CO emissions by modifying boiler control program instead of changing the boiler design [13].

The [14, 15] analyze the influence of moisture content of wood on thermal efficiency and flue gas losses of the boiler. Based on the mathematical model and the conducted experiments, it was concluded that the moisture content in wood has a negative influence on the thermal efficiency of the boiler and increases in flue gas losses. They also gave mathematical expressions for boiler thermal efficiency and flue gas losses based on moisture content in wood and flue gas temperature. Wood chip stove design was analyzed in [16]. Based on three different moisture contents of wood chips, varying fuel feed rate and air excess they gave mathematical expressions for combustion efficiency as a function of excess of air.

The effect of biomass moisture content on combustion and emissions has been the subject of a number of investigations [17-20]. A number of papers have studied emissions from the combustion of biomass with varying moisture content. In [21] authors investigate the effect of moisture content on combustion of wood logs with the conclusion that emissions of the particulate matter increased with increasing wood moisture. The NO_x emissions were not affected by fuel moisture, only by the nitrogen content in fuel. Lukač *et al.* [22] defines mathematical dependencies of NO_x and CO emission generation from a biomass fired boiler.

Determination of emission factors for CO, NO_x, and SO_2 from combustion of wooden and various sorts of agricultural biofuels in a commercially available small scale pellet boiler are given in [23]. Results show the significant influence of operating conditions and experimental procedure, namely for CO. Literature data are mostly consistent in emission factors for NO_x and SO_2, but CO data significantly differ due to the choice of appliance and the experimental procedure.

Performance of the wood chip boiler heating plant (combustion characteristics and emissions), based on experimental tests and mathematical modelling, are given in [24]. The influence of wood chips quality on emission behavior of the boiler are given in [25].

Emission reduction and optimization of efficiency by improving control of combustion process and biomass feeding control are given in [13, 26].

Particulate matter removal from biomass fired boilers has been analyzed in [27, 28].

The aims of this paper were to evaluate the influence of moisture content of wood chips on thermal efficiency and flue gas losses of the boilers of the same construction in actual operating conditions during acceptance tests, and to analyze pollutant emissions (CO, NO_x, and PM). Based on measured parameters mathematical equations were created to calculate both thermal efficiency and flue gas losses of the boiler.

Experimental investigations

Test sites were located in different cities in Serbia. The experimental research was carried out on 22 biomass boilers burning wood chips as fuel with same construction characteristics (model HPKI-R). The manufacturer of the boilers was Gilles, Austria (now Hargassner, Austria). All boilers were connected to the local district-heating network.

The plant consists of wood chip storage, fuel conveyors, boiler and a thermal energy storage tank.

The boilers tested were shell boilers, fig. 1, with a moving step grate for drying, gasification and combustion of the fuel and ash transport from the combustion chamber. The automatic under grate ash discharge transfers the ash from the boiler base via an ash auger into an ash bin. The primary and secondary air are regulated by combustion air fans and a frequency controlled flue gas fan. Boiler output is regulated by flue gas temperature, a lambda probe, the combustion chamber and boiler temperature. The nominal useful heat output of the boilers was in the 450-2000 [kW] range. For particulate emission control boilers were equipped with multicyclones except boilers with useful heat output higher than 1000 [kW]. These boilers have an electrostatic precipitator (ESP) for particulate matter emission control. These types of particulate matter emission controls are typical for these boiler types [17, 27, 28].

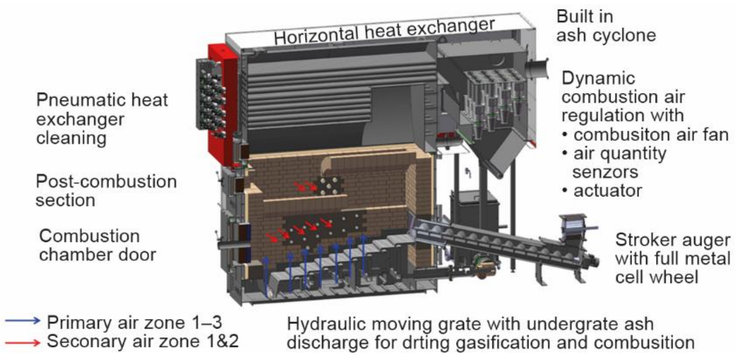


Figure 1. Boiler design [29]

Figure 2 shows the influence of the moisture content of wood chips on the boiler's thermal efficiency and useful heat output provided by the boiler manufacturer for the tested boiler types (HPKI-R). Diagrams in fig. 2 show an increase in both thermal efficiency and useful heat output up to a moisture content of 35%. With further increases in wood chip moisture content there is an evident decrease in these two parameters.

The useful heat output and thermal efficiency of the boilers was determined according to:

– EN 12953-11 – Shell boilers – Part 11: Acceptance tests,
– EN 12952-15 – Water-tube boilers and auxiliary installations – Part 15: Acceptance tests.

Emission measurements were carried out according to:

– EN 15259 – Air quality – Measurement of stationary source emissions – Requirements for measurement sections and sites and for the measurement objective, plan and report,
– EN 14789 – Stationary source emissions – Determination of volume concentration of oxygen – Standard reference method: paramagnetism,
– EN 14792 – Stationary source emissions – Determination of mass concentration of nitrogen oxides – Standard reference method: chemiluminescence,

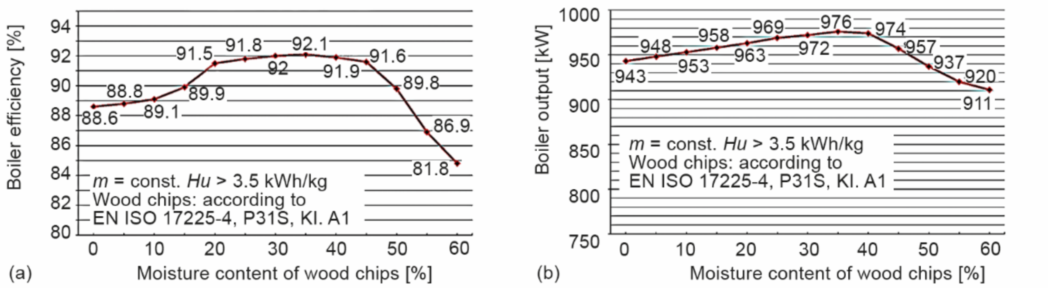


Figure 2. Manufacturer boiler diagrams [29]; (a) biomass boiler HPKI-R, 700–1000 kW and (b) biomass boiler HPKI-R, 950 kW

– EN 15058 – Stationary source emissions – Determination of the mass concentration of carbon monoxide – Standard reference method: non-dispersive infrared spectrometry,
– ISO 9096 – Stationary source emissions – Manual determination of mass concentration of particulate matter,
– EN 13284-1 – Stationary source emissions - Determination of low range mass concentration of dust - Part 1: Manual gravimetric method, and
– EN ISO 16911-1 – Stationary source emissions. Manual and automatic determination of velocity and volume flow rate in ducts – Manual reference method.

The envelope boundary for all experiments encompassed the entire water system (normal envelope according to EN 12953-11).

The measurement of gaseous components in flue gases (O_2, CO, and NO_x) was done with HORIBA PG-250A gas analyzer (with Buhler PCS smart conditioning system), while the sampling of particulate matter was done with isokinetic sampler Zambelli (control unit 5006DL and sampling pump ZB1 Timer). Weighting of the filters before and after sampling was done with Kern analytical balance ABJ 220-4M.

Useful heat output was determined measuring pressure and temperature of the water on the inlet and outlet side and hot water flow, according to:

$$Q_N = \dot{m}(h_2 - h_1) \tag{1}$$

Thermal efficiency was determined by indirect method measuring of all heat losses: flue gas losses, loss due to unburned CO, losses due to radiation and convection, and losses due to enthalpy and unburned combustibles in ash and flue dust. The main losses are flue gas losses, and they focus most of the attention. Flue gas losses were calculated:

$$Q_{(N)\mathrm{G}} = \dot{m}_\mathrm{F} \mu_\mathrm{G} \bar{c}_{p,\mathrm{G}} (t_\mathrm{G} - t_\mathrm{r}) , \tag{2}$$

where t_r = 25 °C is the reference temperature according to EN 12953-11.

Thermal efficiency was calculated:

$$\eta_{(N)B} = 1 - \frac{Q_{(N)\mathrm{G}}}{Q_{(N)\mathrm{Ztot}}} - \frac{Q_{RC}}{Q_{(N)\mathrm{Ztot}}} - \frac{Q_\mathrm{Ash} + Q_{FA}}{Q_{(N)\mathrm{Ztot}}} = 1 - l_{(N)\mathrm{G}} - l_{(N)\mathrm{RC}} - l_{(N)SF} , \tag{3}$$

where $Q_{(N)\mathrm{Ztot}}$ [kW] is the heat input proportional to fuel burned according to EN 12953-11.

Fuel samples were taken for all boiler tests in order to determine proximate and ultimate analysis. Fuels were analyzed according to accredited procedures.

Software packages IBM SPSS Statistics and MICROSOFT OFFICE EXCEL were used to establish correlation between moisture content and flue gas temperature and boiler thermal efficiency and flue gas losses.

Results and discussion

During all boiler tests, a representative sample of wood chips was taken for further proximate and ultimate analysis using appropriate standard methods. An accredited laboratory performed ultimate and proximate wood chips analysis. The results of the wood chips analysis are shown in tab. 1.

Table 1. Proximate and ultimate analysis of wood chips

No.	NCV [kJkg^{-1}]	GCV [kJkg^{-1}]	*W* [%]	*A* [%]	*V* [%]	C_{fix} [%]	C [%]	H [%]	O [%]	N [%]	S [%]
1	11821	13009	35.40	1.46	50.92	12.22	32.96	4.21	25.60	0.22	0.15
2	10187	11362	38.23	0.91	51.48	9.37	31.59	4.11	24.90	0.12	0.14
3	12980	14560	25.86	2.30	60.04	14.10	37.94	4.15	29.33	0.21	0.09
4	11557	13225	33.04	2.27	54.14	12.83	34.98	3.74	25.69	0.20	0.08
5	11016	12706	34.05	1.12	54.52	11.43	32.83	3.90	27.95	0.15	0.03
6	11366	13048	33.94	1.15	54.08	11.98	33.22	3.88	27.70	0.11	0.04
7	13260	14716	24.25	1.90	60.30	15.45	37.37	4.36	31.98	0.14	0.02
8	13164	14678	24.02	1.70	60.70	15.28	36.95	4.44	32.78	0.11	0.02
9	12986	14475	25.37	1.10	59.95	14.68	36.65	4.40	32.38	0.10	0.02
10	10494	12163	36.87	1.08	51.91	11.22	31.40	3.49	27.01	0.14	0.04
11	11601	13228	30.86	1.65	55.90	13.24	33.88	3.97	29.42	0.22	0.05
12	11700	13348	31.82	1.16	55.45	12.73	34.33	3.96	28.61	0.12	0.05
13	10177	11880	37.71	3.59	48.17	14.12	30.53	3.55	24.20	0.42	0.03
14	10810	12485	36.00	2.86	48.88	15.12	31.75	3.62	25.40	0.37	0.03
15	12996	14552	22.59	1.83	62.39	15.02	38.11	4.57	32.65	0.25	0.02
16	12140	13279	27.80	2.01	58.99	13.21	35.47	4.14	30.41	0.17	0.02
17	13020	14605	24.97	1.66	61.93	13.10	37.09	4.43	31.72	0.13	0.01
18	11851	13508	30.13	1.72	58.23	11.64	34.25	4.19	29.44	0.27	0.06
19	14139	15677	19.21	1.00	67.31	13.48	40.76	4.86	33.92	0.24	0.05
20	11321	13006	33.15	1.53	54.96	11.89	33.29	3.98	27.80	0.25	0.06
21	11851	13512	31.68	1.71	56.31	12.01	33.14	4.04	29.27	0.10	0.05
22	11820	13507	32.65	0.84	54.70	12.65	32.97	4.05	29.39	0.10	0.04
min.	**10177**	**11362**	**19.21**	**0.84**	**48.17**	**9.37**	**30.53**	**3.49**	**24.20**	**0.10**	**0.01**
max.	**14139**	**15677**	**38.23**	**3.59**	**67.31**	**15.45**	**40.76**	**4.86**	**33.92**	**0.42**	**0.15**
avg.	**11921**	**13479**	**30.44**	**1.66**	**56.42**	**13.04**	**34.61**	**4.09**	**28.98**	**0.19**	**0.05**

The moisture content of the wood chips was 19.21-38.23% with an average value of 30.44%. Net calorific values (NCV) varied between 10177 and 14139 kJ/kg with an average value of 11921 kJ/kg.

Experimental results given in tab. 1 show a strong negative linear correlation between moisture content and net calorific value (r = –0.967), *i.e.* an increase in moisture content of wood chips lead to a decrease of net calorific value. This affects fuel consumption and the amount of energy released in the combustion chamber. Higher moisture content in wood chips cause longer drying times in the combustion chamber *i.e.*, decrease in combustion temperature. This is in accordance with the obtained negative correlation (r = –0.432) between the moisture content of wood chips and the flue gas temperature.

Table 2 presents the results of the boiler experimental investigations. As shown, boiler efficiency was between 88.78% and 94.06% with an average value of 91.63% and flue gas losses of 5.89-11.13% with an average of 8.22%. Flue gas temperature was between 121.83 °C and 188.44 °C with an average value of 149.13 °C.

Table 2. Results of experimental investigations

No.	Q_N [kW]	$\eta_{(N)B}$ [%]	$l_{(N)G}$ [%]	$\dot{m}_F$ [kgh^{-1}]	t_G [°C]	O_2 [%]	PM* [mgm^{-3}]	CO* [mgm^{-3}]	NO_x* [mgm^{-3}]
1	1022.7	91.76	8.09	345.6	157.46	5.31	97.08	148.17	136.58
2	813.9	91.54	8.28	312.8	140.72	6.68	99.55	61.68	135.67
3	892.6	91.56	7.67	270.0	142.85	6.54	137.60	999.46	130.11
4	1002.1	91.72	7.87	341.6	139.13	6.59	108.80	494.48	148.77
5	459.9	91.60	8.26	137.5	149.89	7.17	76.83	13.95	125.59
6	470.3	91.69	8.17	140.4	141.28	8.04	77.16	10.30	138.18
7	533.6	89.98	9.91	158.0	187.57	5.90	91.13	16.19	140.65
8	535.9	90.91	8.96	159.5	173.54	5.77	109.70	40.50	139.00
9	539.9	89.36	10.49	162.7	188.44	7.02	108.30	111.73	156.94
10	871.5	91.76	8.18	325.2	139.65	6.99	121.20	16.23	149.74
11	1171.3	91.63	8.33	396.0	159.22	5.19	109.70	0.00	144.03
12	926.1	91.21	8.68	320.0	147.97	7.30	110.30	116.78	127.92
13	559.5	92.76	7.17	218.5	123.87	7.54	27.16	36.44	162.98
14	573.3	92.49	7.41	209.2	124.58	7.96	62.14	126.79	172.19
15	1183.6	92.79	7.11	357.8	128.82	7.30	65.22	146.47	154.65
16	1506.5	91.67	8.21	488.9	161.58	4.51	17.09	147.85	145.73
17	504.3	88.78	11.13	152.3	172.19	9.32	108.60	55.77	123.82
18	1038.1	90.37	9.56	340.9	162.63	7.82	110.10	0.00	148.90
19	1003.4	92.89	7.03	277.2	138.11	6.48	104.10	145.39	117.54
20	1084.7	92.00	7.92	375.1	156.70	4.20	72.82	88.77	153.50
21	2585.1	94.06	5.89	859.7	121.83	5.69	11.92	43.59	193.95
22	2435.7	93.43	6.50	816.1	122.73	6.90	8.47	143.90	194.42
min.	**459.9**	**88.78**	**5.89**	**137.5**	**121.83**	**4.20**	**8.47**	**0.00**	**117.54**
max.	**2585.1**	**94.06**	**11.13**	**859.7**	**188.44**	**9.32**	**137.60**	**999.46**	**194.42**
avg.	**987.0**	**91.63**	**8.22**	**325.7**	**149.13**	**6.65**	**83.41**	**134.75**	**147.31**

* Dry basis, reference conditions reference O_2 content was 11% for boilers 15, 16, 21, and 22 and 13% for the remaining boilers)

Statistical analysis of the experimental results given in tab. 2 shows a positive correlation of the moisture content of wood chips with useful heat output (r = 0.037) and boiler thermal efficiency (r = 0.290). There is also a positive correlation between the moisture content of wood chips and fuel consumption (r = 0.146).

There is a negative correlation of the moisture content of wood chips with flue gas losses (r = 0.276) and flue gas temperature ($r = -0.432$). Regarding fig. 2, the moisture content of wood chips was 19.21-38.23%, tab. 1, the obtained positive correlation of the moisture content of wood chips with thermal efficiency and useful heat output are in accordance with manufacturer data. Also, this applies for the negative correlation of the moisture content of wood chips with flue gas losses. By increasing the moisture content of wood chips up to 35%, boiler thermal efficiency value also increases *i.e.*, flue gas losses decrease.

There is positive correlation between flue gas temperature and flue gas losses (r = 0.874) and negative with useful heat output (r = –0.444) and boiler thermal efficiency (r = –0.867), as expected.

Correlation analysis was performed on the data from tab. 2 to obtain expressions for forecasting boiler thermal efficiency $\eta_{(N)B}$ [%] and flue gas losses based $l_{(N)\mathrm{G}}$ [%] on the moisture content of wood chips W [%] and flue gas temperature t_G [°C]. Linear and non-linear expressions were considered because they gave the highest coefficient of determination.

Expressions for boiler efficiency calculation:

$$\eta_{(N)B} = 100.878 - 0.024W - 0.057t_\mathrm{G}, \ R^2 = 0.760 \tag{4}$$

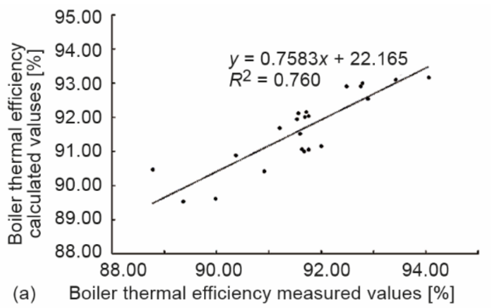
$$\eta_{(N)B} = 101.774 + 0.084W - 0.002W^2 - 0.089t_\mathrm{G} + 0.0001t_\mathrm{G}^2, \ R^2 = 0.762 \tag{5}$$

Expressions for flue gas loss calculation:

$$l_{(N)\mathrm{G}} = -1.292 + 0.029W + 0.058t_\mathrm{G}, \ R^2 = 0.776 \tag{6}$$

$$l_{(N)\mathrm{G}} = 0.626 - 0.140W + 0.003W^2 + 0.062t_\mathrm{G} - 9.59 \cdot 10^{-6} \cdot t_\mathrm{G}^2, \ R^2 = 0.780 \tag{7}$$

Graphical representation of results obtained using eqs. (4)-(7) is given in fig. 3(a) for eq. (4) and 3(b) for eq. (5), and fig. 4(a) for eq. (6) and 4(b) for eq. (7).



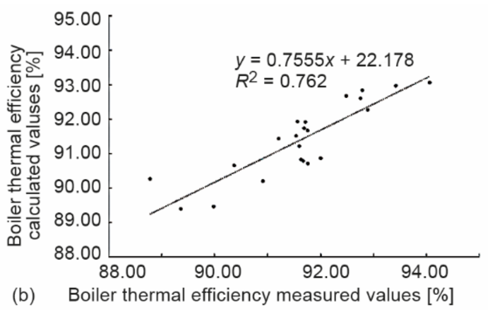


Figure 3. Graphical representation of results obtained using eqs. (4) and (5)

As given in tab. 3, the average value of boiler thermal efficiency, based on measured values, Column I, tab. 3, was 91.63%. The average value of thermal efficiency of the boiler

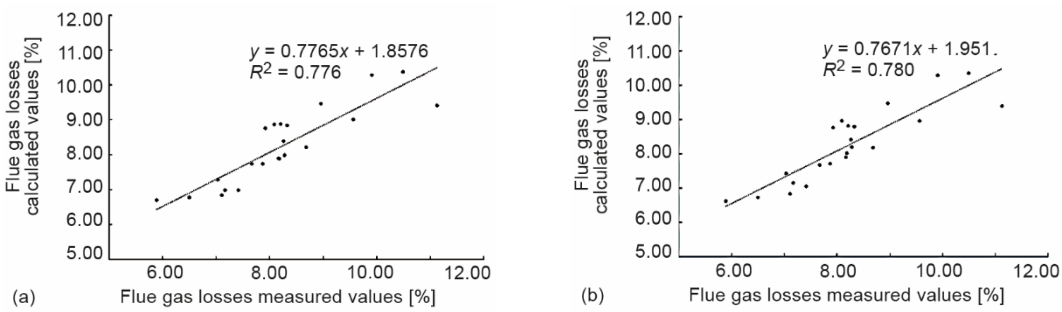


Figure 4. Graphical representation of results obtained using eqs. (6) and (7)

calculated using linear eq. (4) was 91.65%, Column II, tab. 3, and using non-linear eq. (5) was 91.41%, Column III, tab. 3. The absolute value of relative difference for boiler thermal efficiency calculated using eq. (4) was 0.54% and using eq. (5) 0.53%, Column IV and V, tab. 3, respectively. The standard error of the linear model is 0.544 and of the non-linear 0.541. Analysis of particular values of boiler thermal efficiency experimentally determined and calculated using eqs. (4) and (5) shows a difference of –1.68-0.89%, average –0.01%, for eq. (4) and a difference –1.48-1.13%, average 0.22%, for eq. (5).

Concerning flue gas losses, as given in tab. 3, the average value of flue gas losses based on measured values, Column VI, tab. 3, was 8.26%. The average value of flue gas losses calculated using linear eq. (6) was 8.24%, Column VII, tab. 3, and using non-linear eq. (7) was 8.26%, Column VIII, tab. 3. The absolute value of relative difference for flue gas losses calculated using eq. (6) was 5.47% and using eq. (7) 5.16%, Column IX and X, tab. 3, respectively. The standard error of the linear model is 0.531 and of the non-linear 0.520. Analysis of particular values of flue gas losses experimentally determined and calculated using eqs. (6) and (7) shows a difference of –0.84-1.71%, average –0.02% for eq. (6) and a difference of –0.86-1.74%, average –0.04% for eq. (7).

There is good agreement between the calculated and measured data, tab. 3, therefore the correlations obtained can be used for the calculation of thermal efficiency and flue gas losses for the given wood chips boiler construction (model HPKI-R).

Results of the emission measurements obtained during the experiments are given in tab. 2 in biomass combustion processes, the dependence between the emission of NO_x and the N_2 content in the biomass is known [6]. Temperatures in the combustion chamber during experiments were between 718 and 1062 °C and below 1300 °C which is temperature above thermal and prompts NO_x formation. The NO_x emissions were between 117.54 and 194.42 mgNm^{-3} at reference conditions and mainly resulted from wood chip oxidation (fuel-bound NO_x). These are typical NO_x emission values for wood fuels. The statistical analysis of the results given in tab. 2, shows that NO_x emissions have a weak positive correlation with moisture content of wood chips (r = 0.308).

Emissions of CO were below 150 mgNm^{-3} at reference conditions except in two cases (experiment Number 3 and 4). Boilers 3 and 4 were in the same boiler room. Emissions of CO for these two cases were 999.46 mgNm^{-3} and 494.48 mgNm^{-3} at reference conditions, respectively. These boilers have similar thermal efficiency and flue gas losses, tab. 2. The reason for such high CO emissions should be sought primarily in the characteristics of the wood chips. Namely, an increase in fine particle content of the wood chips led to an increase of CO and particulate matter emissions [25]. Fine particles and moisture content of the wood chips

Table 3. Boiler efficiency and flue gas losses calculated from measured values and calculated using eqs. (4)-(7)

	I	II	III	IV	V	VI	VII	VIII	IX	X
No.	$\eta_{(N)B}$ [%][a]	$\eta_{(N)B}$ [%][b]	$\eta_{(N)B}$ [%][c]	Δ I and II [%]	Δ I and III [%]	$l_{(N)G}$ [%][d]	$l_{(N)G}$ [%][e]	$l_{(N)G}$ [%][f]	Δ VI and VII [%]	Δ VI and VIII [%]
1	91.76	91.05	90.71	0.77	1.15	8.09	8.87	8.95	9.61	10.68
2	91.54	91.94	91.52	0.44	0.02	8.28	7.98	8.19	3.64	1.05
3	91.56	92.11	91.94	0.61	0.41	7.67	7.74	7.67	0.95	0.04
4	91.72	92.15	91.92	0.47	0.22	7.87	7.74	7.72	1.71	1.96
5	91.60	91.52	91.22	0.09	0.41	8.26	8.39	8.41	1.56	1.88
6	91.69	92.01	91.74	0.35	0.06	8.17	7.89	7.90	3.47	3.33
7	89.98	89.60	89.46	0.42	0.58	9.91	10.29	10.29	3.84	3.81
8	90.91	90.41	90.20	0.55	0.78	8.96	9.47	9.46	5.69	5.63
9	89.36	89.53	89.40	0.19	0.04	10.49	10.37	10.35	1.11	1.36
10	91.76	92.03	91.67	0.30	0.09	8.18	7.88	8.01	3.71	2.03
11	91.63	91.06	90.83	0.62	0.88	8.33	8.84	8.79	6.09	5.54
12	91.21	91.68	91.44	0.52	0.25	8.68	8.21	8.17	5.38	5.84
13	92.76	92.91	92.61	0.16	0.16	7.17	6.99	7.15	2.57	0.34
14	92.49	92.91	92.67	0.46	0.20	7.41	6.98	7.05	5.83	4.87
15	92.79	92.99	92.85	0.22	0.06	7.11	6.83	6.82	3.87	4.05
16	91.67	91.00	90.79	0.73	0.96	8.21	8.89	8.82	8.23	7.43
17	88.78	90.46	90.26	1.90	1.67	11.13	9.42	9.39	15.37	15.61
18	90.37	90.88	90.66	0.57	0.32	9.56	9.01	8.96	5.71	6.27
19	92.89	92.54	92.27	0.37	0.67	7.03	7.28	7.42	3.49	5.60
20	92.00	91.15	90.87	0.92	1.23	7.92	8.76	8.76	10.58	10.63
21	94.06	93.17	93.07	0.94	1.05	5.89	6.69	6.61	13.63	12.27
22	93.43	93.10	92.97	0.35	0.49	6.50	6.77	6.72	4.20	3.35
min.	**88.78**	**89.53**	**89.40**	**0.09**	**0.02**	**5.89**	**6.69**	**6.61**	**0.95**	**0.04**
max.	**94.06**	**93.17**	**93.07**	**1.90**	**1.67**	**11.13**	**10.37**	**10.35**	**15.37**	**15.61**
avg.	**91.63**	**91.65**	**91.41**	**0.54**	**0.53**	**8.22**	**8.24**	**8.26**	**5.47**	**5.16**

[a] calculated value based on measured values, [b] calculated value based on measured values using eq. (4), [c] calculated value based on measured values using eq. (5), [d] calculated value based on measured values, [e] calculated value based on measured values using eq. (6), [f] calculated value based on measured values using eq. (7)

make the fuel bed on the grate compact which makes it difficult for primary air to penetrate into the bed increasing the amount of unburned fuel and higher emissions of CO [3]. in some cases, wood chips may contain parts of bark, sticks and twigs which can increase not only emission of CO but emissions of NO_x and particulate matter [3]. Statistical analysis of the experimental results given in tab. 2 shows a weak negative correlation of the moisture content of wood chips with emissions of CO (r = –0.183). But this negative correlation has a same trend as obtained correlations of flue gas losses and flue gas temperature with moisture, which is in agreement with manufacturer data.

Emissions of particulate matter were 96.24 $mgNm^{-3}$ at reference conditions (average value) for boilers that have multicyclones for particulate matter removal and below 20 $mgNm^{-3}$ at reference conditions for boilers that utilize ESP for particulate matter removal. Emission values are primarily affected by the share of fine particles in the wood chips and regular maintenance of particulate matter removal devices. These results are expected and show that these particulate matter removal devices can be used to reduce emissions of particulate matter in these boiler types.

Conclusions

This paper presents the results of the experimental investigation of 22 boilers in Serbia burning wood chips as fuel. All boilers were of the same construction. Based on experimental research, it was observed that the moisture content of wood chips has an impact on the heating value of wood chips and on the performance of the boiler plant.

This paper analyzes the influence of moisture content on boiler thermal efficiency and flue gas losses. The analysis shows a positive correlation between moisture content of the wood chips and useful heat output and boiler thermal efficiency. There is also positive correlation between the moisture content of wood chips and fuel consumption and a negative correlation between the moisture content of wood chips with flue gas losses and flue gas temperature. The obtained correlations between the moisture content of wood chips and thermal efficiency and useful heat output are in accordance with the boiler manufacturer data.

Further, experimental research provided grounds for establishing a correlation to calculate boiler thermal efficiency and flue gas losses based on moisture content of wood chips and flue gas temperature. A strong coefficient of determination of expressions was obtained, what could imply that given expressions for boiler thermal efficiency and flue gas losses might be successfully used for quick and approximate determination of these parameters.

The general conclusion of the research is that the obtained correlations could be used to define boiler thermal efficiency and flue gas losses for the considered wood chip boiler types. The derived methodology of correlation forming is applicable for boiler plants burning wood chips on a moving grate.

The results of the emission measurement shows that emissions of NO_x are mainly a result of the nitrogen content of the wood chips (fuel-bound NO_x). The particulate matter emissions show that values are primarily affected by the share of fine particles in wood chips and proper maintenance of removal devices. Regarding emissions of CO, in some cases values were very high. The reason for these high values are primarily due to the characteristics of the wood chips.

Further investigations should comprise experiments conducted over a longer period of time with constant heat output of the boiler. This will provide a better understanding of wood chip characteristics, and their influence on boiler performance and pollutant emissions. Additionally, expressions with a significantly better coefficient of determination could be obtained.

Nomenclature

A – ash content in wood chips (mass fraction), [%]
C – carbon content in wood chips (mass fraction), [%]
C_{fix} – fixed carbon content in wood chips (mass fraction), [%]
$\bar{c}_{p,G}$ – integral specific heat between t_G and t_r of flue gas, [kJkg^{-1}K^{-1}]
CO – emission of carbon monoxide at reference conditions, [mgm^{-3}]
GCV – gross calorific value of wood chips, [kJkg^{-1}]
H – hydrogen content in wood chips (mass fraction), [%]
h_1 – water enthalpy at average inlet temperature, [kJkg^{-1}]
h_2 – water enthalpy at average outlet temperature, [kJkg^{-1}]
$l_{(N)G}$ – flue gas loss, [%]
$l_{(N)RC}$ – loss due to radiation and convection, [%]
$l_{(N)SF}$ – loss due to enthalpy and unburned combustibles in ash and flue dust, [%]
$\dot{m}$ – water mass-flow, [kgs^{-1}]
$\dot{m}_F$ – wood chips mass flow (fuel consumption), [kgs^{-1}, kgh^{-1}]
N – nitrogen content in wood chips (mass fraction), [%]
NCV – net calorific value of wood chips, [kJkg^{-1}]
NO – emission of nitrogen oxides (as NO_2) at reference condition, [mgm^{-3}]
O – oxygen content in wood chips (mass fraction), [%]
O_2 – oxygen content in flue gasses, [%]
PM – emission of particulate matter at reference conditions, [mgm^{-3}]
$Q_{(N)G}$ – flue gas loss, [kW]
$Q_{(N)Ztot}$ – total heat input, [kW]
Q_{Ash} – losses due to enthalpy and unburned combustibles in ash, [kW]
Q_{FA} – losses due to enthalpy and unburned combustibles in flue dust, [kW]
Q_N – useful heat output, [kW]
Q_{RC} – losses due to radiation and convection, [kW]
r – coefficient of correlation, [–]
R^2 – coefficient of determination, [–]
S – sulfur content in wood chips (mass fraction), [%]
t_G – flue gas temperature, [°C]
t_r – reference temperature (= 25 t), [°C]
V – volatile content in wood chips (mass fraction), [%]
W – moisture content of wood chips (mass fraction), [%]
Δ – relative difference, [%]

Greek symbols

μ_G – flue gas mass to fuel mass ratio, [kgkg^{-1}]
$\eta_{(N)B}$ – thermal efficiency, [%]

References

[1] Ilić, M., *et al.*, The State of Biomass Energy in Serbia, *Thermal Science*, *8* (2004), 2, pp. 5-20
[2] Lundgren, J., *et al.*, Experimental Studies During Heat Load Fluctuations in a 500 KW Wood-Chips Fired Boiler, *Biomass and Bioenergy*, *26* (2004), 3, pp. 255-267
[3] Lundgren, J., *et al.*, Experimental Studies of a Biomass Boiler Suitable for Small District Heating Systems, *Biomass and Bioenergy*, *26* (2004), 5, pp. 443-453
[4] Carroll, J., Finnan, J., Emissions and Efficiencies from the Combustion of Agricultural Feedstock Pellets Using a Small Scale Tilting Grate Boiler, *Biosystems Engineering*, *115* (2013), 1, pp. 50-55
[5] Kougioumtzis, M. A., *et al.*, Combustion of Olive Tree Pruning Pellets Versus Sunflower Husk Pellets at Industrial Boiler. Monitoring of Emissions and Combustion Efficiency, *Renewable Energy*, *171* (2021), June, pp. 516-525
[6] Fournel, S., *et al.*, Influence of Biomass Properties on Technical and Environmental Performance of a Multi-Fuel Boiler During On-Farm Combustion of Energy Crops, *Applied Energy*, *141* (2015), Mar., pp. 247-259
[7] Costa, V. A. F., *et al.*, Mass, Energy and Exergy Analysis of a Biomass Boiler: A Portuguese Representative Case of the Pulp and Paper Industry, *Applied Thermal Engineering*, *152* (2019), Apr., pp. 350-361
[8] Bosnjaković, M., Infuence of Moisture Content in Wood Chips on the Boiler Operation, *Proceedings*, 7th International Conference Vallis Aure, Pozega, Croatia, 2020, pp. 91-101
[9] Kuptz, D., *et al.*, Evaluation of Combined Screening and Drying Steps for the Improvement of the Fuel Quality of Forest Residue Wood Chip-Results from Six Case Studies, *Biomass Conversion and Biorefinery*, *9* (2019), 1, pp. 83-98
[10] Yrjola, J., Production of Dry Wood Chips in Connection with a District Heating Plant, *Thermal Science*, *8* (2004), 2, pp. 143-155

[11] Swithenbank, J., *et al.*, Wood Would Burn, *Biomass and Bioenergy*, *35* (2011), 3, pp. 999-1007
[12] Sireesh Kumar, G., *et al.*, Evaluation of Boiler Efficiency of Bio Briquettes by Indirect Method, *International Journal of Mechanical Engineering and Technology*, *7* (2016), 6, pp. 624-633
[13] Quintero-Marquez, A., *et al.*, Improving the Operation of an Automatic Wood Chip Boiler by Optimizing CO Emissions, *Energy and Fuels*, *28* (2014), 3, pp. 2152-2159
[14] Dzurenda, L., Banski, A., Dependence of the Boiler Flue Gas Losses on Humidity of Wood Biomass, *Archives of Thermodynamics*, *36* (2015), 4, pp. 77-86
[15] Dzurenda, L., Banski, A., Influence of Moisture Content of Combusted Wood on the Thermal Efficiency of a Boiler, *Archives of Thermodynamics*, *38* (2017), 1, pp. 63-74
[16] Torres-Fuchslocher, C., Varas-Concha, F., Design and Efficiency of a Small-Scale Woodchip Furnace, *Maderas: Ciencia y Tecnologia*, *17* (2015), 2, pp. 355-364
[17] Sippula, O., *et al.*, Particle Emissions from Small Wood-Fired District Heating Units, *Energy and Fuels*, *23* (2009), 6, pp. 2974-2982
[18] Kazimirova, V., Opath, R., Biomass Combustion Emissions, *Research in Agricultural Engineering*, *62* (2016), SI, pp. S61-S65
[19] Zhao, N., *et al.*, Dynamic Relationships Between Real-Time Fuel Moisture Content and Combustion-Emission-Performance Characteristics of Wood Pellets in A Top-Lit Updraft Cookstove, *Case Studies in Thermal Engineering*, *28* (2021), 3,101484
[20] Bignal, K.L., *et al.*, Release of Polycyclic Aromatic Hydrocarbons, Carbon Monoxide and Particulate Matter From Biomass Combustion in A Wood-Fired Boiler Under Varying Boiler Conditions, *Atmospheric Environment*, *42* (2008), 39, pp. 8863-8871
[21] Price-Allison, A., *et al.*, Emissions Performance of High Moisture Wood Fuels Burned in A Residential Stove, *Fuel*, *239* (2019), Mar., pp. 1038-1045
[22] Lukáč, L., *et al.*, Defining the Mathematical Dependencies of NOx and CO Emission Generation After Biomass Combustion in Low-Power Boiler, *Civil and Environmental Engineering Reports*, *29* (2019), 3, pp. 153-163
[23] Hrdlička, J., *et al.*, Emission Factors of Gaseous Pollutants From Small Scale Combustion of Biofuels, *Fuel*, *165* (2016), Feb., pp. 68-74
[24] Zhang, X., *et al.*, Experimental Investigation and Mathematical Modelling of Wood Combustion in A Moving Grate Boiler, *Fuel Processing Technology*, *91* (2010), 11, pp. 1491-1499
[25] Schön, C., *et al.*, Influence of Wood Chip Quality On Emission Behaviour in Small-Scale Wood Chip Boilers, *Biomass Conversion and Biorefinery*, *9* (2019), 1, pp. 71-82
[26] Valente, L., *et al.*, Emissions Mitigation by Control of Biomass Feeding in an industrial Biomass Boiler, *Energy Reports*, *6* (2020), Feb., pp. 483-489
[27] Oischinger, J., *et al.*, Optimization of the Fractional Collection Efficiencies for Electrostatic Precipitators Used in Biomass-Fired Boilers, *Biomass and Bioenergy*, *141* (2020), Oct., 105703
[28] Jaworek, A., *et al.*, Particulate Matter Emission Control From Small Residential Boilers After Biomass Combustion. A Review, *Renewable and Sustainable Energy Reviews*, *137* (2021), Mar., 110446
[29] ***, Hargassner Biomass Heating Technology, https://hargassner.at

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