Heat-emission analysis of small combustion equipments for biomass

J. Malaťák, L. Passian

Department of Technological Equipment of Buildings, Faculty of Engineering, Czech University of Life Sciences Prague, Prague, Czech Republic

Abstract

Malaťák J., Passian L., 2011. **Heat-emission analysis of small combustion equipments for biomass**. Res. Agr. Eng., *57*: 37–50.

The article addresses the urgent questions regarding the use of biomass as a fuel for combustion equipment of the heat output up to 25 kW. The article is based on the determined elemental analyses of six samples of fuel taken both from the wood mass and herbaceous biomass. These samples underwent the stoichiometric analysis of fuels. After the stoichiometric analysis the heat-emission characteristics were determined on two combustion equipments. The results of carried out elemental and stoichiometric analyses indicate higher values of nitrogen, sulphur and chlorine concentration in herbaceous biomass from agriculture compared to the analyzed wood mass. The selection of combustion equipment is particularly influenced by increased contents of sulphur and chlorine (corrosive behaviour). The net calorific value of the analyzed samples taken from the wood mass is higher than of samples taken from the herbaceous biomass. The net calorific value of fuels from herbaceous biomass is reduced due to a higher content of ashes in the fuel. The results of thermal-emission analyses show higher values of nitrogen oxides, sulphur and chlorine concentrations in the herbaceous biomass compared to the analyzed wood mass. The emission concentrations of carbon monoxide for wood fuels and herbaceous biomass also depend on the type of combustion equipment and setting of combustion air volume. The increased emissions of hydrogen chloride generated by various combustion equipments are primarily caused by the volume of combustion air and the amount of chlorine in the fuel itself. The higher the volume of combustion air brought into the combustion chamber is, the higher the emissions of hydrogen chloride are. Based on the analyses we can also draw a conclusion that the spaces of combustion equipment during combustion should be most burdened with the herbaceous biomass.

Keywords: biomass; chemical analysis; stoichiometric analysis; net calorific value; emission

In the longterm perspective of a sustainable development it is very important to use the energy resources in the most efficient way. Of course also the use of financial "resources" should be optimized in order to reduce the impacts on human health and the environment as much as possible, while the created abundance is becoming more easily available to all parts of the world's population. In the medium-term perspective the climate changes are influenced by the emissions of greenhouse gases from human activities. These changes should be appropriately identified (Hedberg et al. 2002; Malaťák et al. 2007a).

Together with the foreseeable exhaustibility of fossil energy sources the importance of renewable energy sources grows and becomes one of the main

---

Supported by the Internal Grants Agency of the Czech University of Life Sciences Prague, Czech Republic, Project No. 20103001.

conditions of sustainable development not only of agriculture, but also of the whole society. It is indicated that during the last twenty years the global share of herbaceous biomass from agriculture (predominantly it is the wood) in the total consumption of primary energy sources increased by 8%. This increase occurs not only in developing countries where wood is often the only source of energy, especially in rural areas (four fifths of timber extracted in some developing countries are consumed as firewood), but the consumption of wood or fuels based on wood also increases in developed countries.

The fossil fuels can be partially replaced with the solid biofuels; thereby the volumes of waste arising from fossil fuels extraction and processing are reduced, which means a contribution to an increased efficiency of resources. It can be expected that solid fuels based on biomass will reduce the emissions of fossil carbon into the atmosphere and similarly they will be reduced the emissions of greenhouse gasses from anthropogenic activities. Therefore the solid biofuels based on biomass constitute the source of storable solar energy (Jevič et al. 2007; Malaťák, Vaculík 2008; Fiedler, Persson 2009).

If it has to be decided whether the biomass is suitable for burning in a particular type of combustion equipment and to assess the quality of the biofuels from the phytomass in view of their use is necessary to know the properties of biofuels that characterize them sufficiently. From the energy perspective the elemental and stoichiometric analyses are crucial in assessment. The fuel characteristics are supported by the stoichiometric calculations of the combustion processes and any thermal calculation is based on them. They are particularly important for solving many problems in the design practice as well as for controlling the work of existing combustion plants (Jevič et al. 2007; Khor et al. 2007).

In the article other options and limit values of the utilization of solid biomass energy are defined. Therefore it is based on the chemical composition of used fuels, ashes, stoichiometric calculations and the operational parameters of a given type of combustion equipment.

The article aims to formulate such dependencies that as much as possible judge both the combustion process and the quality of combusted fuels from biomass and the combustion equipments. In these analyses there is first of all determined the calorific value of fuel, volume of oxygen (air) required for a complete combustion of fuel, the quantity and composition of flue gas and specific weight of flue gas. The other aim is to determine the thermal emission characteristics and to minimize the emission indicators of the combustion equipments for the utilization of solid biomass energy in accordance with applicable legislation and standards.

MATERIAL AND METHODS

The article is mainly based on elemental and stoichiometric analysis. The resulting values of the stoichiometric analysis are inserted into the equations for pollutant concentrations conversion and into the equations for determining the coefficient of excess air. From the stoichiometric analysis, the theoretical volume concentration of carbon dioxide in dry flue gas, the theoretical volume of dry flue gas and the theoretical volume of air for complete combustion of fuels are inserted into these relations.

In total, 100 measurements were carried out at the combustion equipments for the solid biomass. Twelve measurements that were carried out on two combustion equipments were selected for the assessment of thermal-emission measurements. The analyzed woody fuels and agrofuels according to the ČSN P CEN/TS 15 234 (2007) specification are listed in Table 1.

The determination of the chemical properties is the first task of the solution of the assessed fuel samples as follows:

Table 1. Analyzed wood fuels and herbaceous biomass from agriculture (specification according to ČSN P CEN/TS 15 234, 2007)

Wood fuels	Herbaceous biomass from agriculture
Forest wood chips (spruce) pellets (Ø 10 mm)	energy sorrel pellets (Ø 11 mm)
Poplar pellets (Ø 10 mm)	lucerne pellets (Ø 8 mm)
	knotweed pellets (Ø 11 mm)
	oats grain

- the water content in the received W^r_t(w %, weight percentage) – the method of drying in an oven – the water content in the analytical test sample (ČSN EN 14 774-3, 2010),
- determination of ash content in the as received A^r (w %) (ČSN EN 14 775, 2010),
- determination of calorific value Q (MJ/kg) (ČSN EN 14 918, 2010),
- determination of the content of volatile matter V (w %) (ČSN EN 15 148, 2010),
- determination of total content of carbon (C_t), hydrogen (H_t) and nitrogen (N_t) – instrumental methods (ČSN CEN/TS 15 104, 2006),
- determination of total content of sulphur (S_t) and chlorine (Cl_t) (w %) (ČSN P CEN/TS 15 289, 2006).

The elemental analyses are developed in the form of services provided by the accredited laboratory: Institute for Research and Use of Fuels, Prague-Běchovice, Czech Republic and Institute of Chemical Technology, Prague, Czech Republic. The resulting values of the elemental analysis for individual samples of fuel taken from wood and herbaceous mass are given in Table 2.

The chemical properties are followed by the stoichiometric analysis of combustion processes that supports the characteristics of fuel and constitutes the basis for any thermal calculation. This analysis is particularly important for addressing a range of problems in the design practice or controlling the work of existing combustion equipments. This analysis will identify:

- the net calorific value of the sample Q^r_i (MJ/kg),
- the oxygen (air) volume required for complete combustion of the sample (kg/kg), (m^3N/kg),
- the quantity and composition of flue gas (kg/kg), ($m^3 N/kg$),
- the specific volume of flue gas (V %, volume percentage).

The stoichiometric analysis is converted to the standard conditions and reference oxygen content in the flue gas. Net calorific value of fuel in the calculations is given by the net calorific value of the original sample, i.e. when the sample in the original condition was taken. The resulting values of the stoichiometric analysis are shown in Table 3.

The article aims to assess the theoretical and measured graphic dependence of the carbon dioxide on the oxygen volume in the flue gas with the formulation of excess air coefficient on the original fuel under normal conditions. These dependencies are based on the stoichiometric analysis for the coefficient of excess air in the range of 1–6. The oxygen content in flue gas (O_2) is plotted to the *x* axis and the carbon dioxide (CO_2) content is plotted to the *y* axis. The resulting curve shows the coefficient of excess air. Into the theoretical formulation of the carbon dioxide dependence on the oxygen volume in the flue gas with the formulation of the excess air coefficient on the original sample under normal

Table 2. Chemical analysis as received of solid fuels taken from the woody biomass and herbaceous biomass from agriculture

Sample	Water content (w %)	Ashes (w %)	Combustible matter volatile (w %)	Combustible matter non-volatile (w %)	Gross calorific value (MJ/kg)	Net calorific value (MJ/kg)	Carbon C (w %)	Hydrogen H (w %)	Nitrogen N (w %)	Sulphur S (w %)	Oxygen O (w %)	Chlorine Cl (w %)
Symbol	W^r_t	A^r	V^r	$(NV)^r$	Q^r_s	Q^r_i	C^r_t	H^r_t	N^r_t	S^r_t	O^r_t	Cl^r_t
Forest wood chips (spruce) pellets (Ø 10 mm)	6.79	3.02	75.55	14.64	18.74	17.18	47.37	6.40	0.19	0.01	36.20	0.04
Poplar pellets (Ø 10 mm)	6.17	4.04	75.43	14.36	18.2	16.84	46.16	5.51	0.52	0.03	32.54	0.03
Energy sorrel spruce pellets (Ø 11 mm)	7.95	4.45	70.07	17.53	16.54	15.16	42.7	5.42	1.65	0.11	37.61	0.11
Lucerne pellets (Ø 8 mm)	11.4	8.15	65.16	15.33	16.61	15.34	41.24	4.55	2.85	0.16	31.12	0.22
Knotweed pellets (Ø 11 mm)	5.93	3.99	72.03	18.05	17.62	16.31	45.87	5.33	0.29	0.03	38.49	0.07
Oats grain	8.06	2.35	75.81	13.78	17.17	15.58	42.90	6.40	0.90	0.07	39.26	0.065

Table 3. The stoichiometric analysis of the original fuel samples under normal conditions and reference oxygen content in the flue gas O_r = 11%

Volume combustion		Forest wood chips spruce pellets (Ø 10 mm)	Poplar pellets (Ø 10 mm)	Energy sorrel pellets (Ø 11 mm)
O_{min}	theoretical volume of oxygen for a complete combustion (m^3/kg)	0.99	0.94	0.83
L_{actual}	the actual volume of air for complete combustion (m^3/kg)	9.85	9.39	8.35
n	excess air coefficient (–)	2.10	2.10	2.10
v^s_{sp}	volume quantity of dry flue gas (m^3/kg)	9.75	9.31	8.32
CO_{2max}	theoretical volume of carbon dioxide in dry flue gas (V %)	19.34	19.57	20.26
CO_2	carbon dioxide (V %)	8.06	8.28	8.49
SO_2	sulphur dioxide (V %)	0.00	0.00	0.01
H_2O	water (V %)	10.88	10.26	11.07
N_2	nitrogen (V %)	70.32	70.76	69.79
O_2	oxygen (V %)	9.91	9.95	9.82

		Lucerne pellets (Ø 8 mm)	Knotweed pellets (Ø 11 mm)	Oats grain
O_{min}	theoretical volume of oxygen for a complete combustion (m^3/kg)	0.80	0.88	0.88
L_{act}	the actual volume of air for complete combustion (m^3/kg)	3.83	8.82	4.20
n	excess air coefficient (–)	2.10	2.10	2.10
v^s_{sp}	volume quantity of dry flue gas (m^3_N/kg)	8.03	8.79	8.73
CO_{2max}	theoretical volume of carbon dioxide in dry flue gas (V %)	20.23	20.59	19.54
CO_2	carbon dioxide (V %)	8.52	8.70	8.07
SO_2	sulphur dioxide (V %)	0.01	0.00	0.00
H_2O	water (V %)	10.77	10.39	11.77
N_2	nitrogen (V %)	70.04	70.20	69.54
O_2	oxygen (V %)	9.84	9.89	9.80

conditions the actual values measured on individual combustion equipments are inserted.

At such defined dependencies the percentage of carbon dioxide is graphically determined when combusting the sample as well as the value of the coefficient of excess air that is contained in the flue gas. For practical purposes it is necessary to know the actual value of the oxygen (O_2) content in the flue gas in the measured combustion equipment. An optimal combustion of wood fuels and herbaceous biomass from agriculture should run at the excess air coefficient n = 2.1 (i.e. at 11% of the oxygen content in the flue gas).

All volumes and weights of the combustion air and flue gas are given under so-called normal conditions, i.e. at t = 0°C and pressure p = 101.325 kPa and to the reference content of oxygen in the flue gas O_r = 11%.

The setting of emission concentrations of individual flue gas components is an important task.

Table 4. Technical data of Madur GA-60 analyser (Madur Electronics, Vienna, Austria)

Value/Measurement Principle	Range	Resolution	Sensor accuracy
Ambient temperature/sensor Pt 500	0–100°C	1°C	± 2%
Flue gas temperature	0–1,300°C	1°C	± 5%
Sensor NiCr/Ni (or PtRh/Pt)	0–1,600°C	1°C	± 2%
Electrochemical converter/oxygen (O_2)	0–20.95%	0.01%	± 2%
Electrochemical converter/carbon monoxide (CO)	0–20,000 ppm	1 ppm	± 5%
Electrochemical converter/nitrogen oxide (NO)	0–5,000 ppm	1 ppm	± 5%
Electrochemical converter/nitrogen dioxide (NO_2)	0–800 ppm	1 ppm	± 5%
Electrochemical converter/sulphur dioxide (SO_2)	0–2,000 ppm	1 ppm	± 5%
Pressure	± 50 hPa	0.01 hPa	
Soot number according to Bacharach	0–9	1	
Oxides of nitrogen (NO_x) as NO_2/calculation of NO + NO_2	0–6,000 ppm	1 ppm	
Carbon dioxide (CO_2)/calculation by fuel from CO_{2max} and O_2	0–25%	0.1%	
Excess of air/calculation according to DIN/ÖNORM	1–∞	0.01	

The measurements must be carried out in accordance with ČSN 12 4070 (1990), ČSN 38 5509 (1991), ČSN 07 0240 (1993) and ČSN 44 1310 (2001).

The device Madur GA-60 (Madur Electronics, Vienna, Austria) is used for the determination of emission concentrations of individual flue gas components developed during the combustion of used herbaceous biomass from agriculture and wood mass samples. This is a multi-purpose analyzer of flue gas. Its principle is based on the use of electrochemical converters. The standard equipment includes the converters for analysis of following flue gas components: oxygen (O_2), carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and hydrogen chloride (HCl). Technical data of the analyzer are shown in Table 4.

The resulting concentrations of flue gas in ppm from the analyzer Madur GA-60 are converted into normal conditions and into mg/m^3 and the reference volume of oxygen in the flue gas that is O_r = 11% for the used equipment according to the specified decree and directive. The average resulting concentrations are shown in Table 5 and are compared with the emission limits according to the Directive No. 13, 2006 (this directive applies to appliances with the definition of the hot water boilers for combustion of biomass with manual or automatic supply of nominal output up to 300 kW according to ČSN 07 0240, 1993 and ČSN EN 303-5, 2000). These resulting average values are determined in the whole range of measurement of individual samples.

For the actual measurements two types of representative combustion equipments were selected:

- the retort stoking (lower stoking) – the pellets are pushed by the screw feeder through the retort (knee) into the combustion chamber (Fig. 1),
- the gravity stoking – the pellets are pushed by the screw feeder from the reservoir above the grate on which they then fall down (Fig. 2).

This is automatic hot water combustion equipment with the heat output of 25 kW for solid fuels in the form of pellets intended primarily for heating family houses, cottages, office buildings, small business premises, etc.

Twelve measurements were carried out on the selected combustion equipments.

The resulting values

The resulting values from the chemical analysis of the original samples taken from woody biomass and herbaceous biomass from agriculture are given in Table 2. The values selected from the stoichiometric analysis carried out with the original samples of fuel under normal conditions and at the reference oxygen content in flue gas O_r = 11% are shown in Table 3. In Table 5 the average concentrations from the thermal-emission measurements of analyzed samples

Table 5. The average concentrations of the thermal-emission measurement

	Flue gas temperature	O_2	CO_2	*n* from CO_2	CO (O_r = 11%)	NO (O_r = 11%)	SO_2 (O_r = 11%)	HCl (O_r = 11%)	NO_x (O_r = 11%)
	°C	V %		–	mg/m^3				
Forest wood chips (spruce) pellets (Ø 10 mm) – retort stoking									
Average	280.89	8.80	11.11	1.75	916.00	140.93	31.98	1.73	172.86
Directive No. 13, 2006					2000		60		250
Standard deviation	0.01	0.17	0.14	0.14	0.75	0.35	31.98	139.82	0.35
Forest wood chips (spruce) pellets (Ø 10 mm) – gravity stoking									
Average	231.39	15.27	5.27	3.93	1006.10	415.13	–	412.04	509.39
Directive No. 1, 2006					2000		60		250
Standard deviation	23.23	1.67	1.55	1.28	824.13	72.08	–	71.51	88.40
Poplar pellets (Ø 10 mm) – retort stoking									
Average	251.50	6.94	12.98	1.63	4600.85	116.18	3.87	116.29	143.71
Directive No. 13, 2006					2000		60		250
Standard deviation	47.68	3.56	3.30	0.57	1649.03	64.71	12.46	63.29	78.28
Poplar pellets (Ø 10 mm) – gravity stoking									
Average	290.58	13.96	6.48	3.05	1612.10	316.71	–	314.22	388.46
Directive No. 13, 2006					2000		60		250
Standard deviation	15.01	0.98	0.91	0.60	531.56	48.64	–	48.26	59.66
Energy sorrel pellets (Ø 11 mm) – retort stoking									
Average	292.06	8.48	11.56	1.76	711.78	91.73	45.48	92.70	112.51
Directive No. 13, 2006					2000		60		250
Standard deviation	9.76	1.08	0.99	0.17	145.92	10.80	139.46	25.77	13.24
Energy sorrel pellets (Ø 11 mm) – gravity stoking									
Average	282.67	12.66	7.68	2.66	656.21	106.87	53.18	106.3	131.08
Directive No. 13, 2006					2000		60		250
Standard deviation	12.09	1.03	0.96	0.35	224.13	15.96	339.88	15.84	19.58
Lucerne pellets (Ø 8 mm) – retort stoking									
Average	172.36	10.02	10.04	2.24	2050.39	396.30	246.82	394.55	487.65
Directive No. 13, 2006					2000		60		250
Standard deviation	10.98	3.08	2.85	0.91	407.77	118.58	207.39	120.11	148.29
Lucerne pellets (Ø 8 mm) – gravity stoking									
Average	281.14	12.93	7.43	2.77	3394.56	276.10	49.73	274.24	338.84
Directive No. 13, 2006					2000		60		250
Standard deviation	9.09	90.9	1.31	0.42	379.33	19.43	112.01	19.47	23.99

Table 5. to be continued

	Flue gas temperature	O_2	CO_2	*n* from CO_2	CO (O_r = 11%)	NO (O_r = 11%)	SO_2 (O_r = 11%)	HCl (O_r = 11%)	NO_x (O_r = 11%)
	°C	V %		–	mg/m^3				
Knotweed pellets (Ø 11 mm) – retort stoking									
Average	238.67	11.84	8.43	2.35	1122.87	141.83	–	140.71	173.96
Directive No. 13, 2006					2000		60		250
Standard deviation	21.24	1.43	1.33	0.38	871.79	35.44	–	35.16	43.46
Knotweed pellets (Ø 11 mm) – gravity stoking									
Average	279.49	13.89	6.54	3.18	928.94	242.15	–	240.24	297.00
Directive No. 13, 2006					2000		60		250
Standard deviation	13.51	1.03	0.96	0.52	422.97	93.97	–	93.23	115.25
Oats grain – retort stoking									
Average	205.00	8.57	11.46	1.69	186.86	139.58	–	140.64	171.19
Directive No. 13, 2006					2000		60		250
Standard deviation	3.99	0.78	0.52	0.11	34.68	5.90	–	19.21	7.23
Oats grain – gravity stoking									
Average	234.20	16.55	4.08	6.44	2063.10	698.02	–	692.52	856.14
Directive No. 13, 2006					2000		60		250
Standard deviation	44.87	1.84	1.71	4.73	1933.33	92.6	–	91.34	112.92

are shown that were carried out on two different types of combustion equipment with heat output of 25 kW. The graphic evaluation of carbon monoxide and carbon dioxide in dependence on the excess air coefficient for each sample is shown in Fig. 3.

RESULTS

In the selected samples of fuels in terms of emission concentration the quantities of sulphur, nitrogen and chlorine are the most decisive. At the samples there is an apparent increase in nitrogen emissions since the energy plants have higher values of nitrogen in the fuel (Table 3) compared to the fossil fuels. Especially by an increased content of this element the use of these fuels is restricted.

The selected samples were analysed for the quantity of chlorine in the original fuel. The chlorine concentration in the wood mass is at very low level compared to the vegetal biomass. Namely at the lucerne pellets the concentrations reached above 0.2% share in the fuel. It is clear that the herbaceous biomass from agriculture cannot be assessed according to chlorine content in the wood mass.

Sulphur during the combustion largely goes over into the gas phase as SO_2 and SO_3. The sulphur emissions at heat installations for the use of the solid fuels from renewable resources in terms of limit values usually do not constitute any problem, which is confirmed by the selected samples (Table 3). The corrosive behaviour can constitute the decisive factor of sulphur concentration in the fuel. Other values of the elemental analysis meet the optimal parameters for the use of biofuels in the combustion equipment (Hedberg et al. 2002; Malaťák, Vaculík 2008).

The contents of water and ashes are the most determining for the thermic use of fuels. The range of all water content in the samples is quite low, which has a positive contribution to the net fuels calorific value. The content of ashes in the samples except

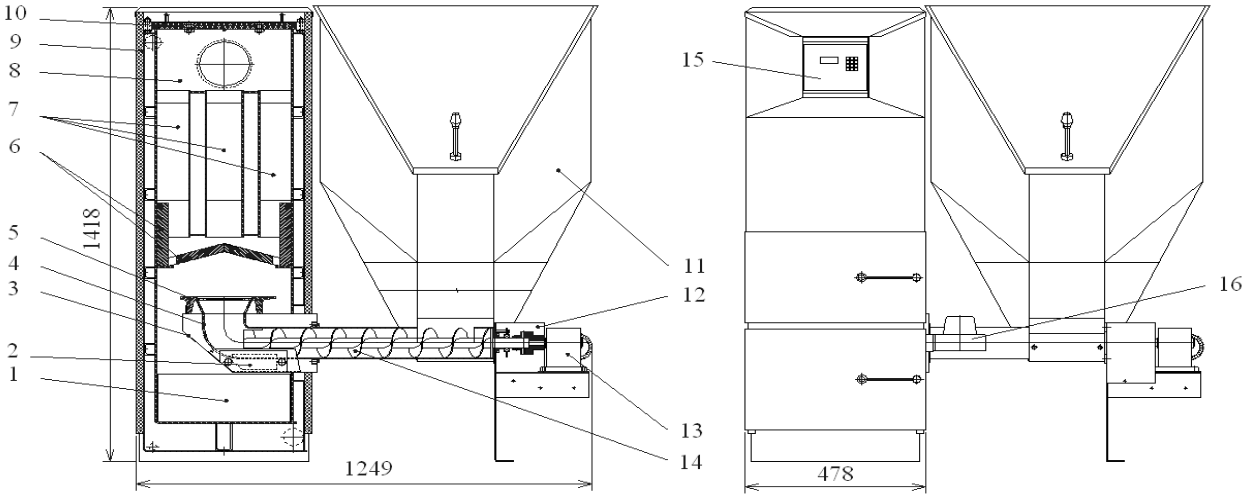

Fig. 1. Diagram of the combustion equipment with lower stoking

1 – ash pan drawer, 2 – cleaning hole of mixer, 3 – air mixer, 4 – retort, 5 –grate, 6 – ceramic reflector, 7 – lamellae of convective section, 8 – flue gas outlet, 9 – combustion equipment insulation, 10 – heating water output, 11– fuel reservoir, 12 – transmission system, 13 – motor, 14 – fuel feeder, 15 – control panel, 16 – fan with the throttle valve

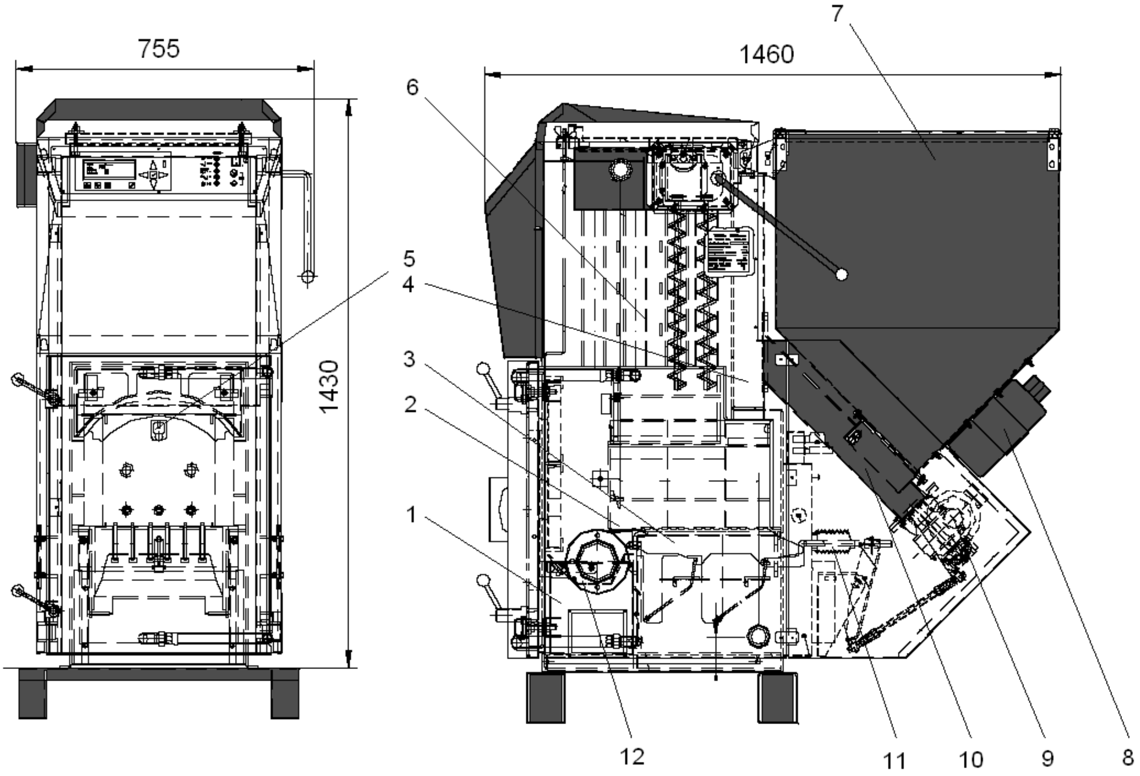

Fig. 2. Diagram of the combustion equipment – gravity stoking

1 – ashes pan, 2 – burner chamber, 3 – grate bar, 4 – fuel fallout, 5 – fuel diffuser, 6 – vortex-generators, 7 – hopper, 8 – fire extinguishing equipment, 9 – transmission with an electric motor, 10 – screw conveyor, 11 – grate bar drive, 12 – ashes trough

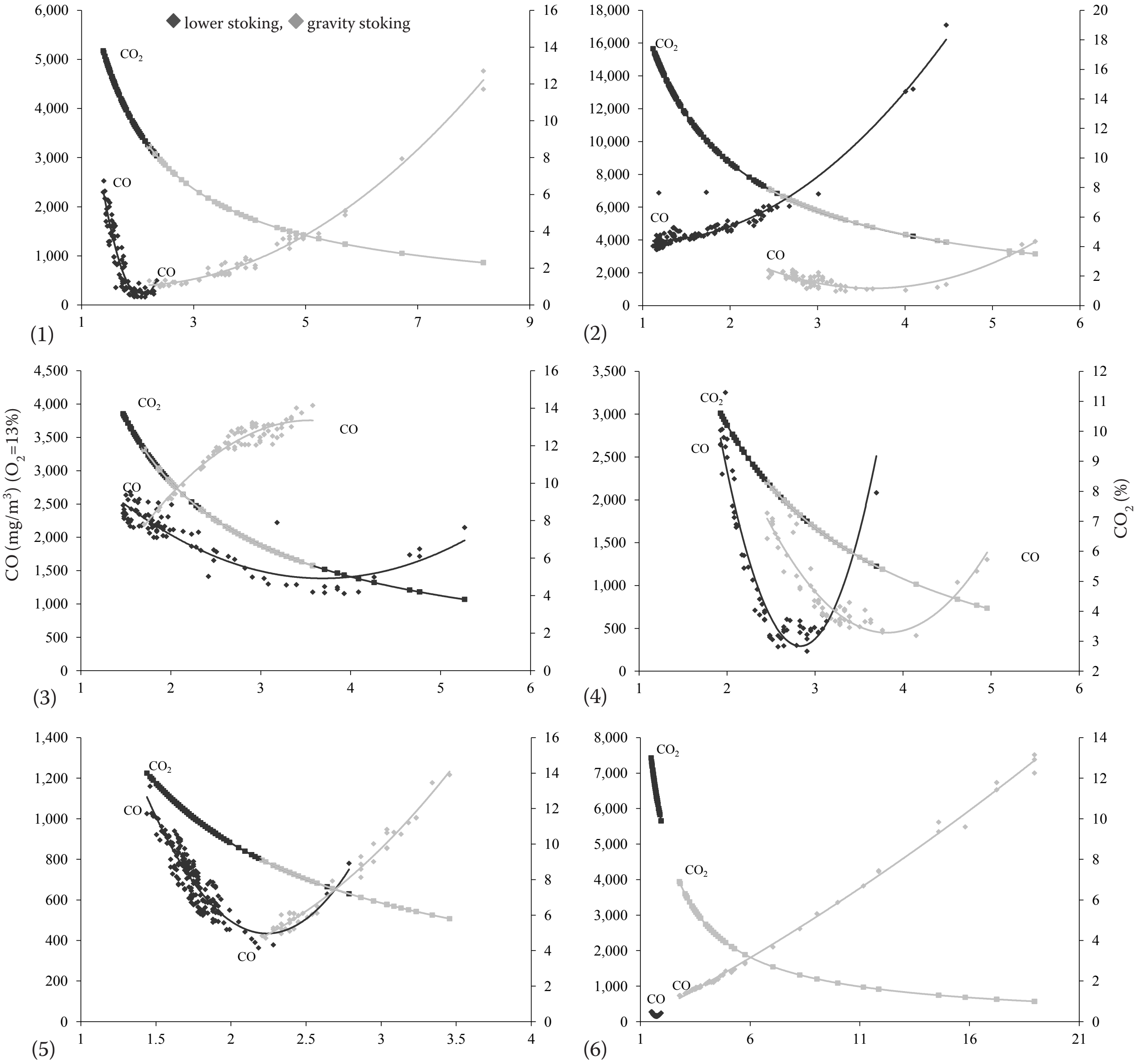

Fig. 3. The measured emission concentrations of CO and CO_2 depending on the coefficient of excess air and combustion equipment

(1) Forest wood chips (spruce) pellets (Ø 10 mm), (2) Poplar pellets (Ø 10 mm), (3) Lucerne pellets (Ø 8 mm), (4) Knotweed pellets (Ø 11 mm), (5) Energy sorrel pellets (Ø 11 mm); (6) Oats grain

the lucerne pellets was also low, which can be seen in elemental analyses of selected samples. By the content of water and ashes the thermal properties of the examined samples are significantly influenced and subsequently both the selection and configuration of the combustion equipment are influenced.

The herbaceous biomass from agriculture contains more ashes compared to the wood mass as it is clear from the results (Table 3), which can cause an increased emphasis on the removal of solid residues after combustion and increase in the the quantity of solid emissions.

The values resulting from the stoichiometric analysis show very good thermal-emission parameters of examined samples. As it results from the stoichiometry of examined fuels the selection and design of the combustion equipment are influenced by the calorific value, water content and energy density. The concentrations of nitrogen, sulphur and chlorine in the samples are relatively very broad, which is confirmed by the analyses of samples. The values resulting from the stoichiometric analysis serve for further necessary calculations of thermal efficiency and heat losses of the combus-

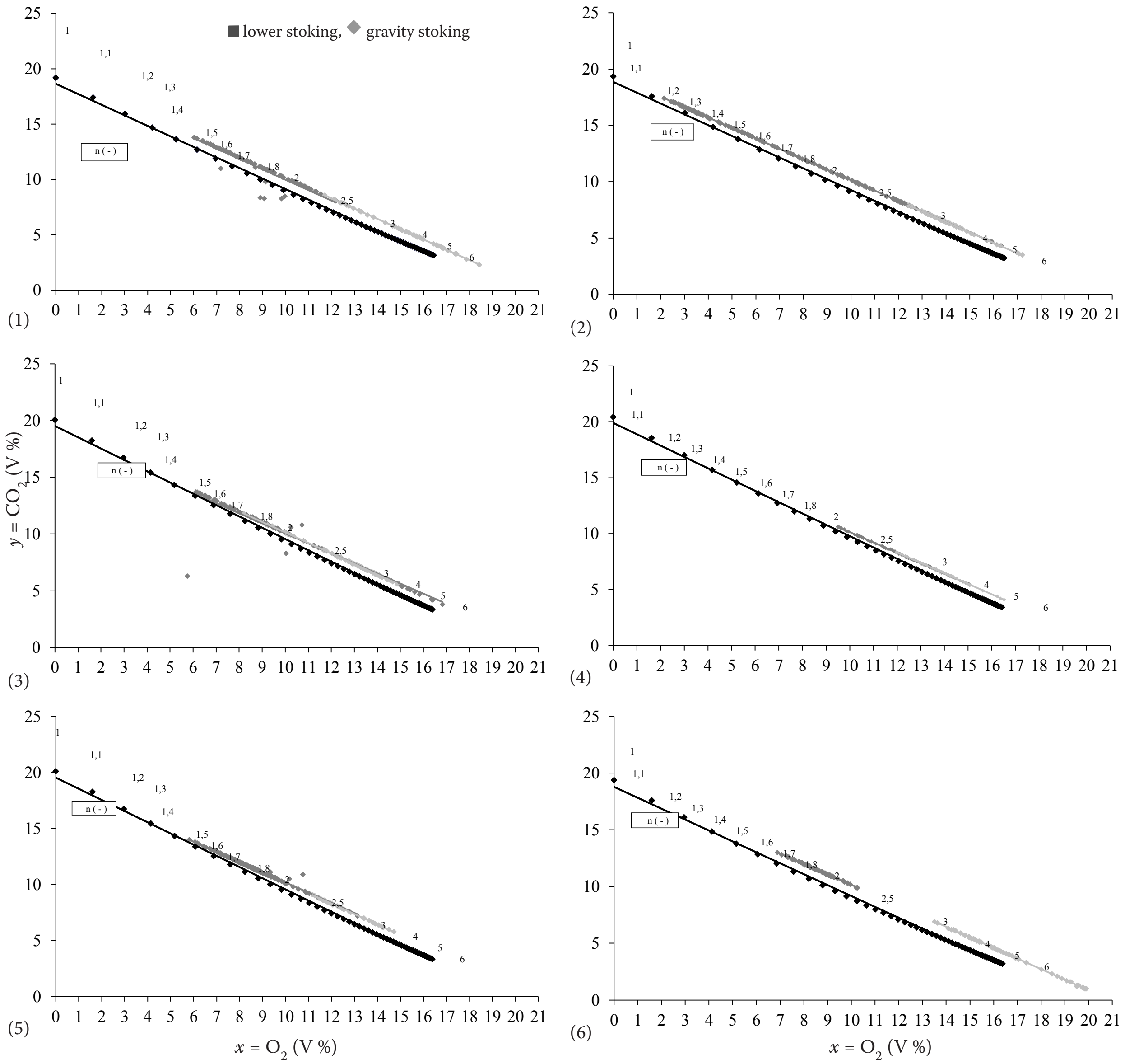

Fig. 4. Theoretical ▲ and actual ■, ◆ graphical dependencies of carbon dioxide on the oxygen volume in the flue gas with the formulation of the coefficient of excess air

(1) Forest wood chips spruce pellets (Ø 10 mm), (2) Poplar pellets (Ø 10 mm); (3) Lucerne pellets (Ø 8 mm), (4) Knotweed pellets (Ø 11 mm); (5) Energy sorrel pellets (Ø 11 mm), (6) Oats grain

tion equipments, but mainly they serve for control and optimization of the combustion equipment.

An important task consists in the assessment of the determined theoretical graphical dependence of carbon dioxide on the volume of oxygen in the flue gas with the formulation of the coefficient of excess air on the original fuel under normal conditions. In the graphic representation of carbon dioxide dependence on the oxygen content in the flue gas with the formulation of the coefficient of excess air on the original sample under normal conditions there are inserted the actual measured values of the combustion equipment. The resulting graphical representation is shown in Fig. 4. The theoretically determined values of carbon dioxide in the graphs are plotted dark blue and real measured values are plotted green for the combustion equipment with lower stoking and light blue for combustion devices with gravity stoking. The statistical analysis is used for further evaluation of resulting differences between the theoretical and actual values.

Despite the slight deviation between the theoretical and measured values these theoretical diagrams can be used for combustion equipments to optimize the setting of combustion fan and exhaust fans. The graphic dependencies expressed in this way can serve for a quick setting of combustion air volume into the combustion chamber. In practice, this results in the optimization of combustion processes especially in the optimal setting of combustion air volume; it may thus also increase thermal efficiencies and reduce heat losses and emissions of the combustion equipment and reduce heat losses and emissions of the combustion equipment.

The resulting average emission concentrations of carbon monoxide on combustion equipment with lower stoking according to the Directive No. 13 (2006) achieve several times higher emission concentrations at the poplar pellets. These emissions are slightly exceeded in case of lucerne pellets. At the combustion equipment with the gravity stoking the emissions at the fuel samples taken from lucerne are exceeded twice and they are slightly exceeded at the oats. In case of other measurements the average emission concentrations of examined samples are optimal. The resulting average emission concentrations of carbon monoxide of individual samples of fuels at the combustion equipments are given in Table 5.

The average emission concentrations of nitrogen oxides exceeding the limits defined by the Directive No. 13 (2006) were determined in case of lucerne pellets and slightly in case of pellets of knotweed at the combustion equipment with lower stoking. Almost at all samples of fuels except the pellets of energy sorrel there are exceeded the emission concentrations of nitrogen oxides in case of combustion equipment with gravity stoking. The fact that the lucerne pellets compared to other examined samples contain the maximum nitrogen in the fuel itself and that the combustion process runs with a large volume of combustion air brought into the combustion chamber and the high temperature of flue gas might be the reasons of increased emissions of nitrogen oxides. The resulting average emission concentrations of nitrogen oxides of individual fuel samples at the combustion equipments are given in Table 5.

At the combustion equipments with the lower fuel supply and in case of lucerne pellets, multiple emissions of sulphur dioxide are measured against the emissions according to the Directive No. 13 (2006). Using this fuel for example in combustion condensing equipment with a higher concentration of sulphur in the fuel would be problematic. Other determined average flue gas emission concentrations at all combustion equipments during measurements are optimal and do not exceed the values according to the Directive No. 13 (2006). The average resulting emission concentrations of sulphur dioxide of individual fuel samples at the combustion equipments are shown in Table 5.

The coefficient of excess air is an important parameter influencing the combustion efficiency. The combustion equipment with lower fuel supply has an optimal average coefficient of excess air in contrast to the combustion equipment with gravity stoking that at all examined samples of fuels has a high value of the coefficient of excess air. The resulting average values of the coefficient of excess air of individual fuel samples at the combustion equipments are given in Table 5.

On combustion equipments the dependencies of carbon dioxide are defined – the product of perfect combustion – on the coefficient of excess air and these dependencies are similar in all cases. With increasing volume of air the concentration of carbon dioxide decreases from the maximum to the minimum concentration, which leads to cooling the flame and dilution of flue gas with the combustion air (Fig. 3).

Carbon monoxide (Fig. 3), the product of incomplete combustion, at every examined sample of fuel and the combustion equipment in the dependence on the coefficient of excess air at first in the area with a very low coefficient of excess air is decreasing down to the optimal values, but after the optimal values of the coefficient of excess air have been exceeded there occurs gradual increase of carbon monoxide up to the maximum concentration. This process can be observed at all fuels except for poplar pellets at the combustion equipment with lower fuel supply and lucerne pellets and oats at the combustion equipment with gravity stoking when at these measurements from the beginning the carbon monoxide is gradually increasing. The reason why a different process of combustion occurs at the fuel samples can be attributed to multiple factors such as the calorific value, the proportion of volatile matter in the sample and the volume of combustion air brought into the combustion chamber. Also in the combustion equipment an insufficient mixing of volatile flammable substances can occur with the combustion air, and thus an insufficient fire penetration on the refractory retorts.

At present the question arises regarding the biomass utilization and generation of dioxins. Dioxin is the name for the two groups of compounds being close to each other regarding their structure and chemical behaviour. These groups are polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF); the first group includes about seventy and the other about one hundred and thirty individual substances. Dioxins belong to the most toxic substances on the Earth and even at concentrations of one to a billion they are life-threatening (they are seventy times more toxic than potassium cyanide). Moreover they are the substances with carcinogenic and teratogenic affects (capable to harm unborn fetus) (Nordin 1994).

The analytical determination of dioxins is a complex and expensive matter (in this country it only is carried out by a limited number of laboratories) and it only can be implemented by means of gas chromatography combined with the mass spectrometry. The measurements are difficult particularly for low concentrations of dioxins (specifically for determination of so called immission values), therefore in this article there only are assessed the emission concentrations of hydrogen chloride that have a direct influence on the formation of dioxins.

At the combustion equipment with lower fuel supply and in case of lucerne pellets several times higher hydrogen chloride emissions were measured compared to other average measured emissions. At the combustion equipment with gravity stoking the hydrogen chloride emissions concentrations are increased at all examined fuels except the energy sorrel pellets. The resulting average hydrogen chloride emission concentrations of individual samples of fuels at the combustion equipments are given in Table 5.

The cause of increased production of hydrogen chloride emissions at individual combustion equipments can be attributed especially to the volume of combustion air and the quantity of chlorine in the fuel itself. The greater is the volume of brought combustion air (excess air coefficient, Table 5), the greater is the generation the hydrogen chloride emissions.

On the basis of analyses we can also draw a conclusion that during the combustion the boiler spaces should be maximally burdened with the vegetal biomass. But it is common that within the phytomass of herbs the city and municipal heating plants are heated with straw most frequently without taking into account that this heating might be inappropriate.

DISCUSSION AND CONCLUSION

The results of elemental and stoichiometric analyses carried out show higher values of nitrogen, sulphur and chlorine concentrations in herbaceous biomass from agriculture compared to the analyzed wood mass. The selection of combustion equipment is particularly influenced by an increased content of sulphur and chlorine (corrosive behaviour). The net calorific value of analyzed samples taken from the wood mass is higher than the net calorific value of the samples taken from the vegetal biomass. The net calorific value of fuel from the herbaceous biomass from agriculture is reduced due to a higher content of ashes in the fuel. Due to a higher content of ashes in the fuel the requirements for removal of solid remnants after combustion are increased and the quantity of solid emissions is also increased.

The coefficient of excess air and water contained in the fuel constitutes the primary factors that significantly influence the work of the combustion equipment. The excess air is required in order to guarantee a perfect combustion. On the other hand it is necessary to take into account the harm caused by a too large air excess. The more air participates in the combustion, the more heat is taken away by the flue gas and consequently the combustion temperature and the efficiency of combustion equipment will decrease plus the heat losses will increase. Therefore it is necessary to use the optimum excess air.

The results of thermal-emission analyses show higher concentrations of nitrogen oxides, sulphur and hydrogen chloride in herbaceous biomass from agriculture compared to the analyzed wood mass. The net calorific value of analyzed samples taken from the wood mass is higher than that of samples taken from vegetal biomass. Regarding the individual emission concentrations of carbon monoxide in case of wood fuels and herbaceous biomass from agriculture these concentrations also depend on the type of combustion equipment.

The cause of an increased hydrogen chloride emissions generated at individual combustion equipments primarily lies in the volume of combustion air and the chlorine content in the fuel itself. The higher volume of combustion air is brought into the combustion chamber, the higher the generation of hydrogen chloride emissions is. Based on the analyses we also can draw a conclusion that during combustion the spaces of boiler should be most burdened with the vegetal biomass.

Washing (leaching) with water is one of the possibilities to reduce these high chlorine concentrations from the herbaceous biomass from agriculture in order to prevent the chlorine effect on the combustion equipment. As recommended by Khor (2007), during the washing an artificial fertilizer rich in chlorine is released (Van der Lans et al. 2000).

Based on the undertaken research of fuels from biomass they contain the trace amounts of sulphur and it is their advantage because no harmful SO_2 air pollutant is generated during combustion. As a result the temperature of dew point of flue gas is reduced because its value is only a function of excess air and of water steam content in the flue gas. This means that for example when burning the wood mass the dew point temperature is significantly lower than during the coal combustion. By the appropriate solution of additional boiler heating surfaces the loss of chimney can be reduced to a minimum without any risk of development of low-temperature corrosion of the additional surfaces (Nordin 1994; Malaťák et al. 2007b; Malaťák, Vaculík 2008).

Therefrom result the requirements for the quality of fuels from biomass. A high quality of pellets from biomass is mainly required for combustion in small combustion equipments. For larger combustion equipments that are equipped with gas cleaning and controlled combustion process, the fuel quality is not critical. It is therefore important to distinguish two types of pellet fuels; it means those for industrial and for small domestic combustion equipments (Obernbergera, Theka 2004).

The use of already available sensors for monitoring the carbon oxide is another way to reduce emissions. The use of sensors for unburnt hydrocarbons especially for carbon monoxide in combination with a lambda probe can provide the combustion equipment with an optimal performance with respect to emissions and the efficiency of combustion equipment regardless the changes in fuel quality and heat outputs.

References

ČSN 12 4070, 1990. Zařízení odlučovací. Metody měření veličin (Dust collecting equipment. Measuring methods of quantity features). Prague, Czech Office for Standards, Metrology and Testing.

ČSN 38 5509, 1991. Plynná paliva. Fyzikální konstanty (Gaseous fuels. Physical constants). Prague, Czech Office for Standards, Metrology and Testing.

ČSN 07 0240, 1993. Teplovodní a nízkotlaké parní kotle. Základní ustanovení (Warm water and low-pressure steam boilers. Basic regulations). Prague, Czech Office for Standards, Metrology and Testing.

ČSN EN 303-5, 2000. Kotle pro ústřední vytápění – Část 5: Kotle pro ústřední vytápění na pevná paliva, s ruční nebo samočinnou dodávkou, o jmenovitém tepelném výkonu nejvýše 300 kW – Terminologie, požadavky, zkoušení a značení (Heating boilers – Part 5: Heating boilers for solid fuels, hand and automatically stocked, nominal heat output of up to 300 kW – Terminology, requirements, testing and marking). Prague, Czech Office for Standards, Metrology and Testing.

ČSN 44 1310, 2001. Tuhá paliva – Označování analytických ukazatelů a vzorce přepočtů výsledků na různé stavy paliva (Solid fuels – Symbols of analytical parameters and formulae for converting the results of analyses of different states of fuels). Prague, Czech Office for Standards, Metrology and Testing.

ČSN CEN/TS 15 104, 2006. Tuhá biopaliva – Stanovení celkového obsahu uhlíku, vodíku a dusíku – Instrumentální metody (Solid biofuels – Determination of total content of carbon, hydrogen and nitrogen – Instrumental methods). Prague, Czech Office for Standards, Metrology and Testing.

ČSN P CEN/TS 15 289, 2006. Tuhá biopaliva – Stanovení celkového obsahu síry a chloru (Solid Biofuels – Determination of total content of sulphur and chlorine). Prague, Czech Office for Standards, Metrology and Testing.

ČSN P CEN/TS 15 234, 2007. Tuhá biopaliva – Prokazování kvality paliva (Solid biofuels – Fuel quality assurance). Prague, Czech Office for Standards, Metrology and Testing.

ČSN EN 14 774-3, 2010. Tuhá biopaliva – Stanovení obsahu vody – Metoda sušení v sušárně – Část 3: Voda v analytickém vzorku pro obecný rozbor (Solid biofuels – Determination of moisture content – Oven dry method – Part 3: Moisture in general analysis sample). Prague, Czech Office for Standards, Metrology and Testing.

ČSN EN 14 775, 2010. Tuhá biopaliva – Stanovení obsahu popela (Solid biofuels – Determination of ash content). Prague, Czech Office for Standards, Metrology and Testing.

ČSN EN 14 918, 2010. Stanovení spalného tepla a výhřevnosti (Solid biofuels – Determination of calorific value). Prague, Czech Office for Standards, Metrology and Testing.

ČSN EN 15 148, 2010. Tuhá biopaliva – Stanovení obsahu prchavé hořlaviny (Solid biofuels – Determination of the content of volatile matter). Prague, Czech Office for Standards, Metrology and Testing.

Directive No. 13, 2006. Směrnice MŽP ČR s požadavky pro propůjčení ochranné známky – Teplovodní kotle pro ústřední vytápění na spalování biomasy (Directive from Ministry of Environment of the CR to the requirements for awarding marks – Hot water boilers for central heating systems for biomass). Prague, MŽP.

Fiedler F., Persson T., 2009. Carbon monoxide emissions of combined pellet and solar heating systems. Applied Energy, *86*: 135–143.

Hedberg E., Kristensson A., Ohlsson M., Johansson Ch., Johansson P., Swietlicki E., Veselý V., Wideqvist

U., Westerholm R., 2002. Chemical and physical characterization of emissions from birch wood combustion in a wood stove. Atmospheric Environment, *36*: 4823–4837.

Jevič P., Hutla P., Malaťák J., Šedivá Z., 2007. Efficiency and gases emissions with incineration of composite and one-component biofuel briquettes in room heater. Research in Agricultural Engineering, *53*: 94–102.

Khor A., Ryu C., Yang Y.B., Sharifi V.N., Swithenbank J., 2007. Straw combustion in a fixed bed combustor. Fuel – The Science and Technology of Fuel and Energy, *86*: 152–160.

Malaťák J., Vaculík P., 2008. Biomass for production energy. Prague, Powerprint Press: 206.

Malaťák J., Gurdil G.A., Jevič P., Pinar Y., Selvi K.C., 2007a. Heat-emission characteristics of some energy plants. The Journal of Agricultural Faculty of Ondokuz Mayis University, *22*: 202–206.

Malaťák J., Karanský J., Altman V., Jevič P., Gálik R., 2007b. Alternative fuels – agricultural waste material utilization. Polnohospodárstvo (Agriculture – Journal for Agricultural Sciences), *53*: 38–48.

Nordin A., 1994. Chemical elemental characteristics of biomass fuels. Biomass Bioenergy, *6*: 339–347.

Obernbergera I., Theka G., 2004. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass and Bioenergy, *27*: 653–669.

Van der Lans R.P., Pedersen L.T., Jensen A., Glarborg P., Dam-Johansen K., 2000. Modelling and experiments of straw combustion in a grate furnace. Biomass and Bioenergy, *19*: 199–208.

Received for publication June 22, 2010
Accepted after corrections April 7, 2011

Corresponding author:

doc. Ing. Jan Malaťák, Ph.D., Czech University of Life Sciences Prague, Faculty of Engineering,
Department of Technological Equipment of Buildings, Kamýcká 129, 165 21 Prague 6-Suchdol, Czech Republic
phone: + 420 224 383 205, e-mail: malatak@tf.czu.cz