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Determination of energy plant chopping quality and emissions while burning chaff

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Abstract. In this paper an analytical review and the results of experimental studies of plant biomass production and its usage as an environmentally friendly local fuel are presented. Such fuels contain virtually no sulfur, and the carbon dioxide released during burning is the natural carbon cycle. An analytical review of experimental research results of growing and burning herbaceous and woody energy plants is given with evaluation and comparison with the emissions of harmful substances into the air while burning these plants. The experimental research results of burning energy plants, such as willows, chopped by the drum, the disc and the screw choppers are presented, and compared with ashen wood burning. The test is carried out in the laboratory boiler, which is designed for burning wood, wood briquettes, and large chips. On determining harmful substance (CO, SO_2, NO, NO_x) emissions into the environment it was concluded that burning of energy plants was better and pollution concentration was lower in case of those chopped bio-fuels (e.g. coarse chopped willow stems, chopped by the drum and screw choppers, and the wood) which were mixed with air while burning.

Key words: Energy plants, environmentally friendly fuel, willow, chaff, burning, pollution, harmful emissions.

INTRODUCTION

The Industrial Revolution of the 18-th century began with the replacement of wood with coal as the fuel source for steam engines; not long after the 19th century the implementation of crude oil as a fuel for lamps, heat, and machines took place (Friedman, 2008). This increased consumption and technology which led to humanity's dependence on fossil fuels.

The Council of Ministers of the European Union agreed in June 1996 that 'global average temperatures should not exceed 2°C above pre-industrial level and that therefore concentration levels lower than 550ppmv CO_2 should guide global limitation and reduction efforts' (Council Directive, 1996).

There are other gases besides carbon dioxide that add to the greenhouse effect. Different greenhouse gases can be compared with each other and are expressed as CO_2 equivalents (CO_{2eq}). These other greenhouse gases include methane, nitrous oxide, and fluorocarbons (CFCs).

To achieve stabilization of atmospheric GHG concentrations, CO_2 as well as other greenhouse gases, such as methane (CH_4), and nitrous oxide (N_2O) should be included. Since the Industrial Revolution, anthropogenic emissions have increased the atmospheric CO_2 concentration from 280ppmv to the current level of around 380ppmv.

Current atmospheric concentration of the three main GHGs, CO_2, CH_4 and N_2O produce a combined radiative forcing that is approximately equivalent to the forcing of CO_2 alone at a concentration of 422ppmv (i.e. 422ppmv $CO_{2eq.}$ accounting for different global warming potentials).

Prior to the Industrial Revolution, the atmospheric concentration of CO_2 was 280 ppm but has increased in the post World War II industry to 367 ppm in 1999 (IPCC, 2001). The concentration of CO_2 in the atmosphere continues to climb at a rate of 1.5ppm yr^{-1} (IPCC, 2001) which has caused a 0.8 ^{0}C increase in global temperatures since 1750 with the most rapid increase occurring after 1970 (Friedman, 2008). The blame can lie predominantly on the current energy system, its energy consumption (Sari & Soytas, 2009) as well as deforestation and land use changes (Scott, 2007). Of the CO_2 emitted into the atmosphere, 75% is derived from the burning of fossil fuels and the remainder comes from deforestation (IPCC, 2001). If energy consumption decreases and the energy system changes, the emissions and their negative effects should be minimized (Sari & Soytas, 2009). If the energy system does not change, models project atmospheric CO_2 concentrations of 540 to 970ppm by 2100 (IPCC, 2001).

The interest in alternative energy sources has increased in recent years due to the realization of the negative consequences of climate change and the depletion of fossil fuel reserves. Renewable energy has a potential to replace petroleum and other fossil fuel energies. Plant biomass is a source of renewable energy and can be burned to produce heat or electricity, be converted into other bio-products and provide environmental services and supply economic benefits (Adegbidi et al., 2003; Keoleian & Volk, 2005). Hydro, bio, geothermal and solar energies are among these alternative energy sources.

Plants under the influence of solar energy from carbon dioxide, water and a small quantity of minerals are capable of synthesizing organic mass. During photosynthesis, the amount of organic matter produced within one year is known as the phytomass gains. Biomass is a local eco-friendly fuel. It contains practically no sulfur, and the carbon dioxide released during burning is part of the natural carbon cycle, which is absorbed in vegetation and in the process of photosynthesis and converted into oxygen.

Renewable energies have lower CO_2 emissions released when compared to fossil fuel energies. Therefore, renewable energies are highly favorable for decreasing the conscious contribution of CO_2 and other GHGs to the atmosphere. The decision, then, on which renewable energy source to endorse is greatly dependent on the availability of resources in the area in question.

Biomass is any plant material that is used to produce bio-energy (Lemus & Lal, 2005). From the time humans discovered fire, biomass has been a primary fuel source.

Plant biomass for energy purposes is a major source of renewable energy. Currently, biomass accounts for about half of the renewable energy used in the European Union (Communication from the Commission, 2005; Renewable energy…, 1996). In the European Union countries, the estimated volume of biomass energy by 2020 will have increased 3–3.5 times, and by 2030 3.5–4.5 times (Renewable energy…, 1996; Šateikis, 2006). It has been predicted that the EU renewable energy consumption in the year 2020 will reach 20% of total domestic consumption, and biomass energy will amount to approximately 13% of total domestic consumption

(65% of the total renewable energy) (Communication from the Commission, 2005; Kryževičienė, 2003). The target for the share of energy from renewable sources in the final consumption of energy in 2020 for Lithuania will be equal to 23% according to the proposed Directive on renewable energy sources (RES) (Kryževičienė, 2003). As early as in 1997 in the countries without significant fossil fuel resources, such as Austria, Sweden, and Finland, biomass energy comprised 12%, 18% and 23%, respectively (Jasinskas & Scholz, 2008).

Plant biomass (wood, straw, energy plants) is one of the most important renewable energy sources in Lithuania and now compose a substantial part of the local fuel. A greater use of the local fuel began due to the implementation of the National Energy Efficiency Program which was established in 1992 and renewed in 1996. New plant biomass use for energy and other purposes was defined in the future prospects by agricultural and rural development strategy program for 2007–2013. In 2005 the amount of plant biomass fuel in Lithuania was 715 thousand toe (tons of oil equivalent), which made up about 94% of the total renewable energy (Jasinskas & Scholz, 2008). Currently, the biomass fuel makes up about 8.2% of all common Lithuanian fuel and energy consumption (Communication from the Commission, 2005; Jasinskas et al., 2008).

Wood fuel is currently the main bio-fuel in Lithuania. In 2005 3,674.5 thousand m^3 of wood and wood waste was produced (Jasinskas & Scholz, 2008). The heat value of wood used for burning is 14.3–15.4MJ kg^{-1} with 15–20% moisture content. The total current consumed wood fuel has the calorific value of 29.76PJ (710 thousand toe) (Communication from the Commission, 2005).

Green biomass energy stock consists of quick-growing trees, bushes, and willow, a tall perennial grass. There are more than 500ha of cultivated willow (*Salix Viminalis*) plantations in Lithuania, which were started to be used as a hard bio-fuel. Therefore, with increasing uptake of renewable energy sources, the research of new technologies and their development is necessary.

The major global environmental problem is the emission of harmful substances into the atmosphere during burning. Burning of the fossil fuel leads to many environmental problems both local (excluding sulfur dioxide, nitrogen oxides, etc.) and global (excluding carbon dioxide and other ‘greenhouse effect’ gas).

Emission limits from fuel burning equipment governed by the Lithuanian Ministry of Environment approved the standards of emissions from fuel burning equipment. These rates are governed by the pollution limit values for burning of bio-fuels, including herbage plants and straw.

Fixed pollutant emission limit values of bio-fuel burning for new and existing installations with a thermal efficiency of 1–50MW (with standard $O_2 = 6\%$ concentrations) (Žaltauskas, 2002) are as follows:

- SO_2 → 2,000mg nm^{-3};
- NO_x → 750mg nm^{-3};
- CO → 1,000–4000mg nm^{-3};
- solid particles → 300–700mg nm^{-3}.

The burning of one ton of straw or grass plants in furnaces produces 30–40kg of ash, while 5–8kg of dust remains in the filter. Straw ash contains about 0.09% of nitrogen, 1% of phosphorus, and 11% of potassium. In addition, ashes have a small amount of heavy metals: copper, zinc, tin, nickel, chromium, cadmium, etc. These ashes can be used as fertilizer because of phosphorus and potassium.

Foreign countries, especially Western European and Scandinavian countries apply various measures to promote the production and use of organic fuel – energy plants – for energy purposes. Lithuania is moving in the same direction (Jasinskas & Scholz, 2008).

A big amount of wood (wood chips) is used as a fuel. Wood chip characteristics as for moisture content, ash content, percentage of fine particles, and particle-size distribution, are essential when wood is used as a fuel or for industrial purposes (Asikainen & Pulkkinen, 1998). For solid bio-fuels particle size distribution is a crucial parameter for an efficient combustion while heating plants (Hartmann et al., 2006) and is also important during storage, as it affects calorific value (Kofman & Spinelli, 1997) and durability (Nellist, 1995). A European standard (EN 14961:2010) defines quality parameters and classification of solid bio-fuels, also for the purpose of increasing the opportunities for international trade. Oversize particles (sticks) should be avoided, because they tend to stick together, hindering the feeding of boilers. For different considerations, fines under 3mm of length (wood dust) should be excluded because they can be a health hazard due to the limitation of air flow during storage, supporting bacteria diffusion, with an increased risk of combustion (Garstang et al., 2002). As stated by some authors (Spinelli et al., 2005), wood chip size depends on chipper type, besides on the tree parts (branches, stems, or logs), tree species, knife setting, screen type, etc. (Alakangas, 2005).

Similar environmental pollution studies for the production and application of energy crops which are used as a fuel in Lithuania are increasingly available.

Study objective is to determine the chopping quality of energy plant stems and harmful emissions into the environment while burning energy plants, prepared by different chopping mechanisms.

MATERIALS AND METHODS

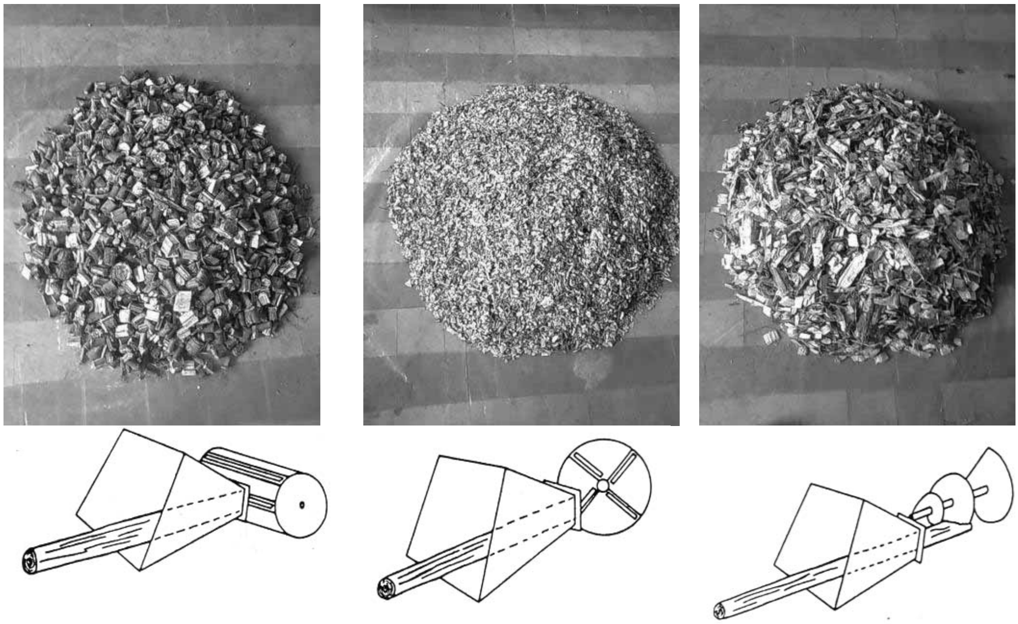
Evaluation of physical-mechanical properties of plant stem chaff

Stem chopping and sampling were carried out according to the methodology used in Germany and Lithuania (Scholz et al., 2006; Jasinskas, 2002). Freshly cut three-year-grown willow stems are chopped.

Willow (*Salix Viminalis)* stem chaff moisture content was determined in the laboratory. The five samples (each of 100g mass) were taken and weighed mixing the chaff of each plant. Samples were dried for 48 hours at the temperature of 105^{o}C. The dried samples were weighed after which the empty cups were weighed. The moisture content and average moisture content of each sample were calculated.

Three types of choppers were used to chop the already cut energy plant stems: a) the drum chopper, b) the disc chopper and c) the screw chopper (Fig. 1). All the choppers are equipped with a blower which conveys the chips into the container through a duct (Scholz et al., 2006).

The drum chopper consists of a rotating drum with knives embedded in 4 longitudinal grooves in the curved surface. Such as in the disc chopper, the knives pass a fixed anvil and the chip size is modified in the same way. The chips produced are less uniform than those from a disc chopper. These choppers are generally used for wood chopping, and they are best suited for the chopping of willow stems (Jasinskas & Scholz, 2008).



a) b) c)

Figure 1. Various types of energy plant chopping mechanisms and the chaff quality: a) the drum chopper; b) the disc chopper; c) the screw chopper.

Three-year-grown willow stems, grown on the Institute test plots, were chopped with the drum, the disc, and the screw choppers. The chopped mass was supplied in bags, from which the chaff samples were taken for determination of their physical-mechanical properties. On comparing the physical-mechanical properties of the stem chaff chopped with different choppers, the chopping machine operating parameters and their chopping quality can be described.

Methodology of chaff fineness evaluation

The willow stem chaff fineness used for fuel must be determined by refinement on the basis of boilers used in the combustion chamber, chaff transport equipment, storage requirements, etc. Furnaces with the required fineness of chaff obtained high combustion efficiency.

Three-year-growth willow stem chaff, chopped by the three types of choppers was used in the experiment. The quality of stem chaff and chaff fineness was defined by the stem chaff fractional composition determination methodology (Scholz et al., 2006; DD CEN/TS 15149-1:2006).

The application of this methodology, used for determining the fractional composition, is based on European Standard (DD CEN/TS 15149-1:2006). 5kg of chaff sample was passed via 40mm diameter sieves with round holes of the following diameters: 63mm, 45mm, 16mm, 8mm, and 3.15mm. While screening each sample, the sieve set was rotated 30 times within a semicircle in a horizontal plane. The remaining-on-sieves mass was weighed separately. The mass left on the different sieves was weighed and calculated in percentages. Each test was replicated three times, and the average mean values of fractional composition and their error values were calculated.

Methodology of determining harmful emissions of willow stem chaff into the environment by burning energy plants prepared by different chopping mechanisms

Boilers fired with solid biofuel fuel combustion and emission level depend on the type of fuel and fuel preparation quality as well as on the boiler characteristics. In order to find the impact of chopper type (drum; disc; screw), the influence of preparation quality of chopped willow stem chaff on combustion and emission formation was studied. Cut ashen wood was used for comparison.

Investigations were carried out in the laboratory of Agricultural Engineering Institute of Lithuanian University of Agriculture; for chaff burning, a low-power (small) boiler for solid-fuel adapted to burn solid biomass, such as wood chips, wood waste, sawdust, pellets, and briquettes was used. During investigation no changes of boiler settings were made and were accepted as constant boiler characteristics. To accomplish the investigations biofuel combustion laboratory had been equipped, the technological scheme of which is shown in Fig. 2.

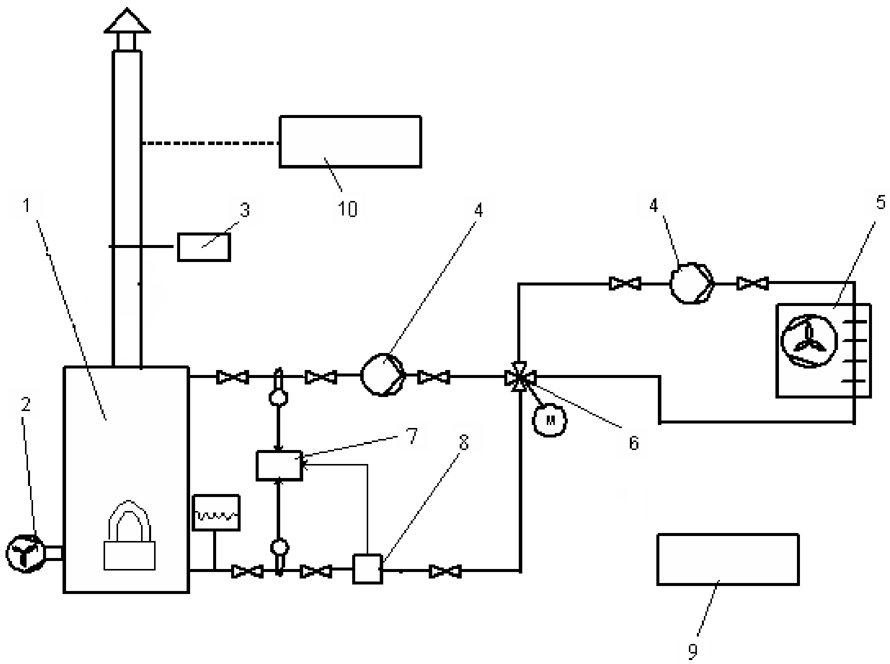


Figure 2. Technological scheme of biofuel combustion laboratory: 1 – solid bio-fuel boiler; 2 – ventilator of boiler fuel furnace; 3 – temperature sensor; 4 – circulating pump; 5 – heater; 6 – valve of automatic control; 7 – heat indicator; 8 – water indicator; 9 – control unit regulator; 10 – combustion gas emission measuring equipment.

The fuel which is in the furnace burns on the fire grate. Air supplies have not been forced during investigations due to determination of the combustion opportunities of willow chaff using similar types of domestic boilers. Investigations were carried out using standard methods (LST EN 303-5:2000).

Laboratory was equipped with a small 10kW solid fuel boiler Marco 1. Fuel burns on furnace fire grate and air for combustion was supplied by fan 2. Boiler temperature sensor was installed in boiler 3 which could help to determine the temperature of the exhaust gas. Pumps 4 ensured water circulation. The system consisted of two control loops: boiler temperature control and boiler load regulation. Heater 5 used for load was Volcano VR1 which had a maximum capacity of up to 30kW. Water fluid circulation was controlled by automatic four-way valve 6 and three-way manually operated valve 7. For heat amount record sensor 8 was equipped. The system was controlled and regulated by block 9. Combustion emission analysis was performed with a special gas analyzer 10.

Harmful emissions were measured by the flue gas analyzer 'UniGas 4000', made by the Italian company Eurotron (Fig. 3). The harmful emissions of CO, SO_2, NO, and NO_x were measured. The values of permissible emissions were regulated by standards (Jasinskas & Scholz, 2008; Žaltauskas, 2002).

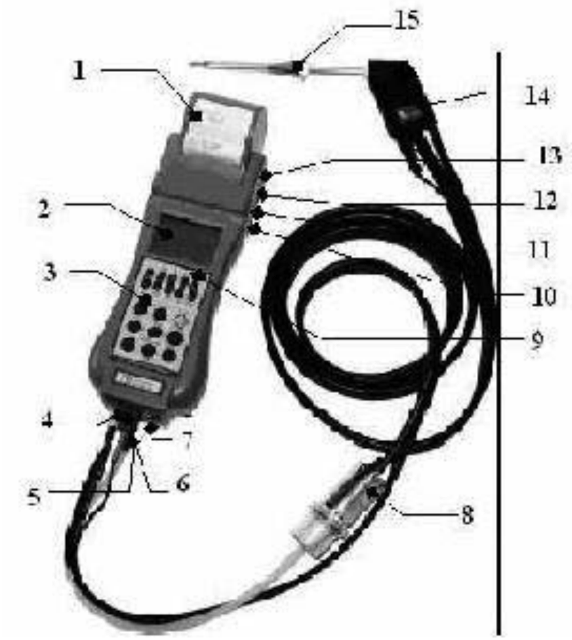


Figure 3. Flue Gas Analyzer UniGas 4000 components: 1 – impact printer; 2 – LCD display; 3 – keyboard; 4 – P1 draft pressure input; 5 – INLET flue gas input; 6 – gas temperature input; 7 – P2–ΔP input; 8 – water trap and line filter; 9 – back light sensor; 10 – T air probe sensor; 11 – battery charger; 12 – other external probe input; 13 – infrared wave interface; 14 – emissions sampling; 15 – a stable sampling position lock.

The device UniGas 4000 is designed as a convenient portable device. The device includes a function of gas analyzers, gas parameters, and the external display. The device consists of the following main parts. The device has an internal 250 MB memory, where all the information is saved. In addition, the device has a light sensor, which responds to ambient lighting conditions and adjusts the graphic display lighting. Device 13 which facilitates the analysis of the data may be connected to a personal computer via an infrared interface and is used to scan the data. P1 connector is connected to the primary air pressure gauge. In order to prevent contamination of the device, gas is properly cooled and water barrier is being constructed with a metal mesh filter. The device is automatically calibrated when it is turned on. It records the external parameters as working zero.

The most important technical characteristics of the gas analyzer UniGas 4000 are shown in Table 1.

Table 1. Technical characteristics of gas analyzer UniGas 4000.

Parameter	Sensor type	Range	Resol.	Max response	Accuracy
O_2	Electrochemical	from 0 to 25%	0.1 %	20 sec.	±0.1 %
CO H_2 compensated to 1,000ppm	Electrochemical	from 0 to 8,000ppm	1ppm	50 sec.	±10ppm.<300ppm. ±4 % to 2,000ppm ±10% > 2,000ppm
CO	Electrochemical	from 0 to 20,000 ppm	1ppm	40 sec.	±10 ppm.<300ppm. ±4 % to 2,000ppm ±10% > 2,000ppm
CO%	Electrochemical	from 0 to 10%		50 sec	±0.01%<0.2%. ±4 % >0.2%
NO	Electrochemical	from 0 to 4,000ppm	1ppm	40 sec.	±5ppm < 125ppm ±4% > 125ppm
NO_2	Electrochemical	frm 0 to 1,00 ppm	1ppm	50 sec.	±5ppm < 125ppm ±4% > 125ppm
NOx	Calculated	from 0 to 5,000ppm	1ppm		
SO_2	Electrochemical	from 0 to 4,000ppm	1ppm	40 sec.	±5ppm < 125ppm ±4% > 125ppm
CO_2	Calculated	0 to 100%	0.1 %		±2 %

Five repetitions of registration of all the process parameters were done for each burning sample. Boiler capacity was determined simultaneously with data recording. During the tests the emission of harmful substances into the environment was determined by burning willow chaff chopped with different choppers and compared with control sample – ashen wood (each sample of 5kg weight). Prior to each test willow chaff moisture content was determined (according to the above mentioned standard methodology).

RESULTS AND DISCUSSION

Evaluation of physical-mechanical properties of willow plant stems chaff

The assessment of the quality of willow stem chaff in accordance with the methodology of the EU countries, using a set of sieves with round holes of different diameters disclosed that the larger part of the chaff was obtained by chopping with drum chopper, and the disc chipper chopped more uniformly, producing the finest willow chaff (Table 2).

Table 2. Plant chaff fractional composition (according to the EU methodology).

Plant	Chopper type	The chopped stem mass left on the sieve, %					
		Ø 63 mm	Ø 45 mm	Ø 16 mm	Ø 8 mm	Ø 3.15 mm	Dust
Willow (3rd year growth)	Drum	1.58 ±1.53	2.19 ±2.02	89.54 ±2.98	6.19 ±1.14	0.81 ±0.37	0.20 ±0.06
	Disc	0.98 ±0.40	0.74 ±0.11	69.24 ±5.67	22.76 ±5.66	5.90 ±0.99	0.39 ±0.129
	Screw	10.17 ±6.25	7.57 ±2.31	76.06 ±6.67	4.88 ±0.78	1.08 ±0.37	0.25 ±0.16

The chaff fineness was shown by accumulated chaff fraction on a Ø 16mm sieve: willow stems were chopped by a drum chopper, 89.5% of the willow chaff mass was left on this sieve, and when these plants were chopped by the disc chopper, much less chaff was left on this sieve – the total of 69.2% of willow chaff mass.

Willow chaff chopped by the screw chopper was also quite large – chaff fraction part was equal to 76.1% of chaff mass accumulated on a Ø 16mm sieve. In the chopped willow chaff there were more than 10% particles of larger than 63mm length, which is not desirable for the bio-fuel of high quality chaff.

Harmful emissions of willow stem chaff due to burning energy plants

Harmful emissions into the environment were determined by burning willow stem chaff, prepared by different chopping mechanisms: drum, disc, and screw choppers (Fig 1). Ashen wood was used for comparison.

For combustion products the gas analyzer UniGas 4000 was used to measure harmful gas emissions during the burning process. For measuring carbon dioxide CO_2 in the laboratory, a small boiler proved problematic (these results are not given). Carbon monoxide CO, sulfur dioxide SO_2, nitrogen monoxide NO, and nitrogen oxide NO_x release into the atmosphere is presented in Table 3. The boiler power used for water heating is shown. All research results have only comparable character between harmful gas emissions while burning in laboratory energy plants, prepared by different chopping mechanisms. During burning the energy plant chaff, prepared by different chopping mechanisms, no setting changes were made in laboratory boiler and they were accepted as constant boiler characteristics. These research results cannot be compared with the results of energy plants burned in other boiler types of great capacity.

The investigation results provided a general tendency that at the end of the combustion process when burning of the energy plant loading finishes to burn (when intensity of burning decreases), all harmful combustion gases have a tendency to decrease.

While burning the energy crops, the maximum carbon monoxide CO concentration was found on burning large willow chaff chopped with screw chopper – 1,815.7mg m^{-3}, and the least CO concentration was identified on burning willow chaff of medium fineness, chopped with drum chopper – 975.7mg m^{-3}.

Sulfur dioxide SO_2 emissions from the combustion of different willow chaff chopped with different choppers and ashen wood were not observed.

Burning of willow chaff, chopped by different chopper types, and evaluation of nitrogen oxides NO_x (nitrogen monoxide, respectively NO) emissions show that most nitrogen oxide emissions have been released by burning small willow chaff (chopped with disc chopper) – 71.4mg m^{-3} (Table 3), and while burning medium and large willow chaff, chopped with drum and screw chippers, nitrogen oxide emissions were from 2.9 to 3.2 times lower (respectively, 25.0 and 22.0mg m^{-3}). While burning ashen wood, emissions of nitrogen oxides were the lowest and reached only 3.6mg m^{-3}.

Table 3. Investigation results of harmful emissions by burning energy plants.

No.	Fuel type, moisture %	Chopper type	CO mg m^{-3}	SO_2 mg m^{-3}	NO mg m^{-3}	NO_x mg m^{-3}	Boiler power kW
1.	Willows (12.5±0.2%)	Screw	–	0	23	34	7.7
2.			3155	0	17	28	6.3
3.			2004	0	12	25	5.5
4.			1267	0	8	13	5.4
5.			837	0	6	10	4.9
Avg			**1,815.7**	**0**	**13.2**	**22.0**	**5.96**
1.	Willows (11.7±0.9%)	Drum	–	0	36	57	7.4
2.			2120	0	24	39	7.3
3.			686	0	9	14	6.5
4.			591	0	5	8	5.2
5.			506	0	5	7	5.0
Avg			**975.7**	**0**	**15.8**	**25.0**	**6.28**
1.	Willows (16.8±1.6%)	Disc	2460	0	57	86	9.8
2.			1103	0	44	69	6.1
3.			1120	0	60	93	6.5
4.			1033	0	31	50	6.5
5.			1817	0	36	59	7.8
Avg			**1,506.6**	**0**	**45.6**	**71.4**	**7.34**
1.	Ashen wood (25.0±0.4%)	Felled wood	896	0	0	0	7.0
2.			2023	0	2	5	6.5
3.			1604	0	4	7	6.0
4.			2555	0	3	5	5.2
5.			1875	0	0	1	5.0
Avg			**1,790.6**	**0**	**1.8**	**3.6**	**5.94**

In the study of harmful gas emissions by burning energy plants, chopped with a different cutter, the energy of power boiler load variation during combustion was determined. It was found out that the boiler had developed an incomplete boiler power from 6.0 to 7.3kW (about 60–73% of the nominal). In order to effectively exploit boiler and get more power, it is recommended not to charge furnace in portions of energy plant chaff but supply the bio-fuel continuously.

In summary, a conclusion can be made that the worst burning occurs when small willow chaff, chopped with disc chopper is used. Combustion of medium and large willow chaff, chopped with drum and screw choppers, polluted the environment much less by providing better combustion efficiency of bio-fuels, because the air access into larger chaff is better ensuring good combustion quality.

CONCLUSIONS

1. The assessment of the fractional composition of willow stem chaff in accordance with the methodology of the EU countries disclosed the fineness of chaff fraction accumulated on a Ø 16mm sieve: willow stems chopped by drum chopper, on this sieve 89.5% of the willow chaff and plants chopped by the disc chopper left much less chaff on this sieve – 69.2% willow chaff mass by weight.

2. It was determined that willow chaff chopped by screw chopper was quite large – the chaff part accumulated on a Ø 16mm sieve was 76.1% by weight of chaff. This chopped mass had more than 10% of larger than 63mm length parts, which is not desirable for high-quality chaff used as bio-fuel.

3. While burning the energy crops, the maximum carbon monoxide CO concentration was found in burning large willow chaff chopped with screw chopper **–** 1815.7mg m^{-3}, and the least CO concentration was identified in burning medium fineness willow chaff chopped with drum chopper – 975.7mg m^{-3}.

4. Burning of willow chaff chopped with different chopper types, and the evaluation of nitrogen oxides NO_x (nitrogen monoxide, respectively NO) emissions show that most nitrogen oxide emissions have been released by burning small willow chaff (chopped with disc chopper) – 71.4mg m^{-3}, and while burning medium and large willow chaff, chopped with drum and screw chippers, nitrogen oxide emissions were 2.9 to 3.2 times lower (respectively 25.0 and 22.0mg m^{-3}).

5. It was found out that in the study of harmful gas emissions by burning energy plants, chopped with a different cutter, the boiler has developed an incomplete boiler power from 6.0 to 7.3kW (about 60–73% of the nominal).

6. In summary, a conclusion can be made that the worst burning occurs when small willow chaff, chopped with disc chopper is used. Combustion of medium and large willow chaff, chopped with drum and screw choppers, polluted environment much less by providing better combustion efficiency of bio-fuels.

REFERENCES

Adegbidi, H. G., Briggs, R. D., Volk, T. A., White, E. H. & Abrahamson, L. P. 2003. Effect of organic amendments and slow-release nitrogen fertilizer on willow biomass production and soil chemical characteristics. *Biomass & Bioenergy* **25**, 389–398.

Alakangas, E. 2005. Properties of wood fuels used in Finland – BIOSOUTH – project. Technical Research Centre of Finland, VTT Processes, Project report PRO2/P2030/05 (Project C5SU00800), Jyväskylä 2005, 90 pp. + app. 10 pp.

Asikainen, A. & Pulkkinen, P. 1998. Comminution of Logging Residues with Evolution 910R chipper, MOHA chipper truck, and Morbark 1200 tub grinder. *Journal of Forest Engineering* **9**(1), 27–36.

Communication from the Commission. 2005. Biomass action plan. Commission of European Communities. Brussels, 7.12.2005 COM 628 final, 58 pp.

Council Directive, 96/29. Euratom, 1996 May, 29 pp.

DD CEN/TS 15149-1:2006. Solid biofuels – Methods for the determination of particle size distribution. Part 1: Oscillating screen method using sieve apertures of 3.15 mm and above.

EN 14961:2010. Solid biofuels – Fuel specifications and classes – Part 1: General requirements (http://www.cen.eu).

Friedman, T. L. 2008. Hot, Flat and Crowded: Why we need a green revolution - and how it can renew America. Farrar, Straus and Giroux, New York.

Garstang, J., Weekes, A., Poulter, R. & Bartlett, D. 2002. Identification and characterisation of factors affecting losses in the large-scale, non ventilated bulk storage of wood chips and development of best storage practices. London: First Renewables Ltd. for DTI. 119 pp.

Hartmann, H., Böhm, T., Jensen, P. D., Temmerman, M., Rabier, F. & Golser, M. 2006. Methods for size classification of wood chips. *Biomass & Bioenergy* **30**(11), 944–953.

IPCC. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jasinskas, A. 2002. Estimation of Physical–mechanical Properties of Tall Growing Bioenergy Plants. Proceedings of the International Conference: *Progressive Eco-Friendly Technological Processes in Agricultural Engineering.* Lithuanian Institute of Agricultural Engineering, 19–20 September 2002. Raudondvaris, pp. 187–194.

Jasinskas, A. & Scholz, V. 2008. Evaluation of technologies of plant biomass harvesting and preparation for fuel: coursebook. Raudondvaris, 74 pp. (in Lithuanian).

Jasinskas, A., Žaltauskas, A. & Kryževičienė, A. 2008. The investigation of growing and using of tall perennial grasses as energy crops. *Biomass & Bioenergy* **32**(11), 981–987.

Keoleian, G. A. & Volk, T.A. 2005. Renewable energy from willow biomass crops: Life cycle energy, environmental and economic performance. *Crit. Rev. Plant Sci.* **24**, 385–406.

Kofman, P. & Spinelli, R. 1997. Storage and handling of willow from short rotation coppice. Forskiningscentret for Skovog Landskab, Hoersholm, Denmark. Report No NEIDK-

Kryževičienė, A. 2003. Potential of Perennial Grasses and their possible local and renewable resources as a biofuel. *Rural Development in 2003*: *set of reports*, 274 pp. (in Lithuanian).

Lemus, R. & Lal, R. 2005. Bioenergy crops and carbon sequestration. *Crit. Rev. Plant Sci.* **24**, 1–21.

LST EN 303-5:2000 (EN 303-5:1999). 2000. Boilers. Part 5. Manually and automatically loaded solid fuel boilers with a nominal power up to 300 kW. Terminology, general requirements, testing and marking.

Matias, J. C. & Devezas, T. C. 2007. Consumption dynamics of primary-energy sources: The century of alternative energies. *Applied Energy* **84**(7–8), 763–770.

Nellist, M. 1995. The effect of particle size on the storage and drying of wood fuels. In. Hudson B., Kofman, P. Ed. Harvesting storage and road transportation of logging residues. *Proceedings of a workshop of IEA-BA-Task XII activity 1.2* held in October 1995 Glasgow, Scotland. FSL, Vejle (Denmark), pp. 59–70.

Renewable energy – power for a sustainable future. 1996. Edited by G. Boyle, Oxford University, 478 pp.

Sari, R. & Soytas, U. 2009. Are global warming and economic growth compatible? Evidence from five OPEC countries. *Appl. Energy* **86**, 1887–1893.

Schneider, U. A. & McCarl B.A. 2003. Economic potential of biomass based fuels for greenhouse gas emission mitigation. *Environ. Res. Econ*. **24**, 291–312.

Scholz, V., Lorbacher, R. F. & Spikermann, H. 2006. Stand der Pflanz – und Erntetechnik für Kurzumtriebsplantagen: Anbau und Nutzung von Bäuen auf landwirtschaftlichen Flächen 1. Fachtagung, Tharandt, 6. und 7. November, 2006. S. 149–156.

Scott, D. S. 2007. Smelling Land: The hydrogen defense against climate catastrophe. Enhanced Edition ed. Canadian Hydrogen Association (www.h2.ca.).

Spinelli, R., Hartsough, B. & Magagnotti, N. 2005. Testing mobile chippers for chip size distribution. *International Journal of Forest Engineering* **16**, 29–36.

Šateikis, I. 2006. Potential of plant biomass cultivation and use for solid fuels and priority of research the present problems. *Agricultural engineering: IAE LUA and LUA research papers*. Raudondvaris, **38**(3), 5–21 (in Lithuanian).

Žaltauskas, A. 2002. Usage of straw as a fuel in Lithuania. Kaunas, 44 pp. (in Lithuanian).