EFFECTS OF BIOMASS COMPOSITION VARIATIONS ON GASIFICATION AND COMBUSTION CHARACTERISTICS

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Abstract. The main aim of this study is to investigate, analyze and compare the gasification and combustion characteristics of different types of pelletized biomass (softwood, herbaceous biomass and agriculture residues) with different contents of cellulose, hemicelluloses and lignin and to obtain cleaner and more effective heat energy production. Kinetic study of the thermo-chemical conversion of biomass pellets includes complex measurements of the biomass weight loss rate at thermal decomposition of biomass and correlating variations of the flame temperature, heat production rates and composition of products with estimation of the correlations between the main characteristics of the pelletized biofuel, biomass weight loss rates, heat energy production and composition of the products. The analysis shows faster thermal decomposition and thermo-chemical conversion of softwood granules (spruce) with a higher heating value and carbon content determining a correlating increase of the heat production rate and the rate of CO_2 production with a higher average volume fraction of CO_2 in the products. The higher heating value of wheat straw lignin promotes higher heat energy production that predominately refers to the char conversion stage. The analysis of the correlation between the nitrogen content in biomass and the NO_x mass fraction in the products evidences that a higher content of nitrogen in biomass pellets leads to higher average and peak values of the mass fraction of NO_x emission.

Keywords: pelletized biomass, heating values, combustion characteristics, heat production rate.

Introduction

Biomass as an environmentally friendly energy source has received a continuously increasing interest from the heat and power producers, as thermo-chemical conversion of biomass can produce less global warming pollution than fossil fuels. At the same time, utilization of different biomass types for controllable energy production is restricted because of wide variations of their bulk and energy density and variations of the moisture content in plant biomass determining unpredictable combustion process characteristics. Predictable energy production at thermal conversion of biomass can be achieved providing densification of biomass as (because) biomass pellets have the increased and fixed energetic and bulk density and the controllable moisture content. However, at nearly equal bulk density and moisture content in biomass pellets, the combustion characteristics are influenced by wide variations of the pellet chemical composition (content of hemicelluloses, cellulose and lignin) determining variations of the biomass weight loss rate during the thermal decomposition and variations of heat energy production at the thermo-chemical conversion of the volatiles. For example [1; 2], the content of cellulose in softwood biomass is about 43-47 %, the content of hemicelluloses 25-27 %, while the content of lignin approaches to 27-28 %. The higher content of cellulose (47-49 %) and hemicelluloses (28-39 %) with the reduced content of lignin 8-11.5 % [2; 3] points to herbaceous biomass (reed canary grass), while the reduced content of cellulose (36-43 %) and lignin (17-24 %) with the higher content of hemicelluloses in comparison with softwood biomass points to willow biomass and agriculture residues [1; 4]. In addition, different biomass types can differ in their elemental composition, determining variations of the carbon, hydrogen and nitrogen content, leading to variations of the produced heat energy and composition of the products [1; 4]. Hence, if different biomass pellets are used as energy resources, there is a need in a detailed experimental study to estimate the effect of variations in the chemical and elemental composition on thermo-chemical conversion. The main goal of this study is to investigate and estimate the impact of the variations of the main characteristics of pelletized biomass (woody, herbaceous biomass and agriculture residues) on the biomass gasification/combustion and heat energy production.

Biomass composition and experimental procedures

In this study, different types of biomass pellets are used representing a wide variation of the main characteristics of densified biomass – woody biomass (spruce sawdust), willow and willow with molasses, agricultural residues (wheat straw), wheat straw lignin, herbaceous biomass (reed canary grass) and a mixture of reed canary grass with spruce (50:50) (Table 1).

The biomass pellets are produced using a laboratory scale pellet mill KAHL 14-175. The bulk density, elemental analysis, ash content and the heating values are determined in accordance with the CEN TC 335 standards. Thermal analysis (TG, DTG, DTA) of biomass samples is made using the Mettler Toledo Star System TOA/SDTA 851, in air and nitrogen atmospheres at a heating rate of 10 K·min^{-1}, an air flow rate of 50 ml/min and a sample mass of 8 mg. To improve the mechanical characteristics of pellets consisting of willow (95 %) and molasses (5 %), the constituents were at first carefully ground ($d = 0.05$ mm) using a ball Mixer mill MM 200, oven dried at 50 ºC and then pelletized. The wheat straw lignin samples are produced by enzymatic hydrolysis (separated hydrolysis and fermentation).

Table 1

Main characteristics of pelletized biomass

Characteristics of biomass	Spruce sawdust	Reed canary grass	Reed canary grass+spruce	Willow pellets	Willow with molasses	Wheat straw pellets	Wheat lignin pellets
Moisture, %	8.1	7.1	8.2	9.1	9.0	10.9	6.4
Ash content, %	0.37	3.39	1.88	1.32	1.70	7.11	6.40
C, % (on DM)	49.1	46.8	47.9	45.3	44.7	41.8	49.7
H, % (on DM)	6.44	6.27	6.34	6.23	6.38	6.15	5.34
N, % (on DM)	0.18	0.57	0.37	0.35	0.39	0.85	1.08
O*,% (on DM)	43.9	43.0	43.5	46.7	46.8	44.1	37.5
HHV, MJ·kg^{-1}	19.6	18.6	19.1	18.0	17.7	16.7	19.6
LHV, MJ·kg^{-1}	18.2	17.2	17.7	16.6	16.3	15.3	18.4
Pellets bulk density, kg·m^{-3}	660 ± 10	683 ± 10	669 ± 10	506 ± 10	666 ± 10	656 ± 10	789 ± 10

* from the difference

The gasification and combustion of different types of pelletized biomass (250-270 g) was experimentally studied using a small-scale pilot device composed of a biomass gasifier and a combustor [5]. Primary and secondary airflows are used to initiate the pelletized biomass gasification and provide the complete burnout of the volatiles and char. The propane burner with controlled stoichiometric propane and air supply into the burner was used as an external heat energy source to initiate the process of biomass gasification. The complex measurements of the biomass gasification and combustion characteristics downstream the swirling flame flow involve local measurements of the flame composition, temperature and combustion efficiency using a gas analyzer Testo-350 XL. The local measurements of the flame temperature are made using thermocouples with a PC data recording system. The heat production from the combustion of pelletized biomass is estimated from the calorimetric measurements of the water-cooled channel sections by using PC-20. In order to estimate the biomass weight loss rate (dm/dt) during the thermo-chemical conversion of biomass, time-dependent variations of the biomass layer height (dL/dt) in the gasifier at the biomass gasification are measured using a test facility, which consists of a moving rod supplied with a pointer.

Results and discussion

1. Thermal analysis of different biomass samples

The results of the thermo-gravimetric analysis have shown that thermo-chemical conversion of biomass pellets develops as a two- stage process with the primary stage of thermal decomposition of the main biomass constituents (hemicelluloses, cellulose and lignin) and the next stage of char conversion with thermal decomposition of lignin residue [1] determining the formation of two main peaks of the weight loss rate at 575-595 K and 650-720 K (Table 2). As follows from the data of the DTG analysis (Table 2), the higher weight loss rate at the primary stage of thermal degradation is typical for pellets of spruce sawdust and willow biomass with a slight decrease of the weight loss rate during the char conversion stage. An additive of molasses (5 %) to willow biomass significantly reduces the weight loss rate (~2 times), with a slight (~10 %) decrease of the weight loss rate at the char conversion stage, while the amount of ash residues increases. The reduced rate of thermal decomposition with the maximum weight loss rate at lower temperatures in comparison with spruce sawdust pellets is observed for pellets of reed canary grass (R.c.g.), which have a higher content of hemicelluloses, which are the most thermo-labile biomass constituents. The maximum weight loss rate at the char conversion stage for R.c.g. is observed at a significantly decreased temperature, if compared with spruce pellets that can be related to reduced condensation of carbonized species. With the aim to improve the main characteristics of R.c.g. at thermo-chemical conversion of biomass, spruce sawdust was added to the biomass of R.c.g. (50:50). The DTG analysis of thermal degradation has shown that an addition of spruce sawdust to R.c.g. results in an increase of the weight loss rates at the thermal decomposition and char conversion stages. However, the temperatures increase too that corresponds to the peak value of the weight loss rates (Table 2). The thermo-destruction of wheat straw lignin shows a reduced weight loss rate at the primary stage of biomass gasification with the correlating increase of the weight loss rate at the char conversion stage indicating that a lower amount of the volatiles is released at thermal destruction of cellulose, as observed in [6]. Hence, at the higher content of lignin in biomass the mass loss at the char conversion stage dominates.

Table 2

Thermogravimetric characteristics of biomass samples at the gasification/char conversion stage

Characteristics of biomass	Gasification stage			Char conversion stage			Ash remain, %
	dm/dt_{max}, mg/min	T_{max}, K	Weight loss, %	dm/dt_{max}, mg·min^{-1}	T_{max}, K	Weight loss, %	
Spruce sawdust	1.85	593	75.9	0.82	716	23.6	0.5
Reed canary grass	1.03	584	71.2	0.75	675	25.0	3.6
R.c.g+spruce	1.11	594	71.3	0.84	694	26.0	2.6
Willow pellets	1.74	593	75.6	0.97	699	22.9	1.5
Willow with molasses	0.90	585	72.6	0.89	679	24.8	2.5
Wheat straw pellets	0.97	578	65.9	0.80	657	26.4	7.4
Wheat straw lignin pellets	0.99	585	59.0	0.93	689	33.9	7.0

To compare the amounts of the produced heat at different stages of thermo-chemical conversion for different biomass samples, a DTA analysis of the produced heat energy was made [3; 6]. The results have shown that the highest amount of the produced energy at the gasification stage is observed for the spruce sawdust pellets (ΔH_1 = 101.5 kJ·mol^{-1}), approaching to 67.4 % of the total energy produced at their thermo-chemical conversion. The heat produced for the R.c.g. pellets is about 80 % of the heat amount at the thermo-chemical conversion of spruce pellets. The absolute (ΔH_1) and relative ($\Delta H_1/\Delta H$) indicators of the heat production for the samples of the spruce sawdust mixture with R.c.g. reduce by ~15 % in contrast to the total heat energy (ΔH) produced at the thermo-chemical conversion of spruce sawdust pellets, while the total heat energy (ΔH) for the pellets of the R.c.g. mixture with spruce sawdust reduces by ~6-10 %. The highest total amount of the produced heat is observed for the lignin samples with the minimum value of the produced heat energy at the primary stage of thermo-chemical conversion of the volatiles (55.1 %). However, the absolute indicators of ΔH_1 were only by ~4 % less than $\Delta \mathrm{H}_1$ for the spruce samples and higher than ΔH_1 for other biomass samples. This evidences that the products of lignin gasification have the highest heating value among all investigated samples. The relative variation of heat energy release ($\Delta H_2/\Delta H$) due to char combustion for all samples was 1.3-1.5 times higher than the weight loss rate at this stage of thermo-chemical conversion. An opposite situation is observed at the gasification stage, when the relative indicators of the energy release rate were 1.1.-1.2 times lower than the weight loss rate. This allows concluding that the heat energy produced at the stage of char conversion is significantly higher than the heat energy of the gasification products.

2. Combustion and emission characteristics of biomass samples

The results of the DTG analysis have shown that the processes of biomass thermo-chemical conversion are strongly influenced by the biomass characteristics with direct influence on the main combustion characteristics at thermo-chemical conversion of the biomass samples, providing variations of the heat production rates, flame temperature, biomass weight loss rates, formation and composition of gaseous products. The experimental study of the processes of thermal decomposition of different biomass types developing in the gasifier has revealed a significant diversity of the weight loss rates depending on the biomass composition (Fig. 1, a). The wheat straw pellets show faster thermo-chemical degradation, when the thermo-chemical conversion process lasts for about 1280 s. The lower mass loss rate is observed for the pellets of reed canary grass and willow, when the thermo-chemical conversion of the pellets lasts for about 2400-2600 s. The higher mass loss rates during the gasification stage are observed for the mixture of R.c.g. with spruce and willow pellets, while the pellets of wheat straw lignin have a pronounced char conversion stage that is in good agreement with the TG analysis results presented in Table 2.

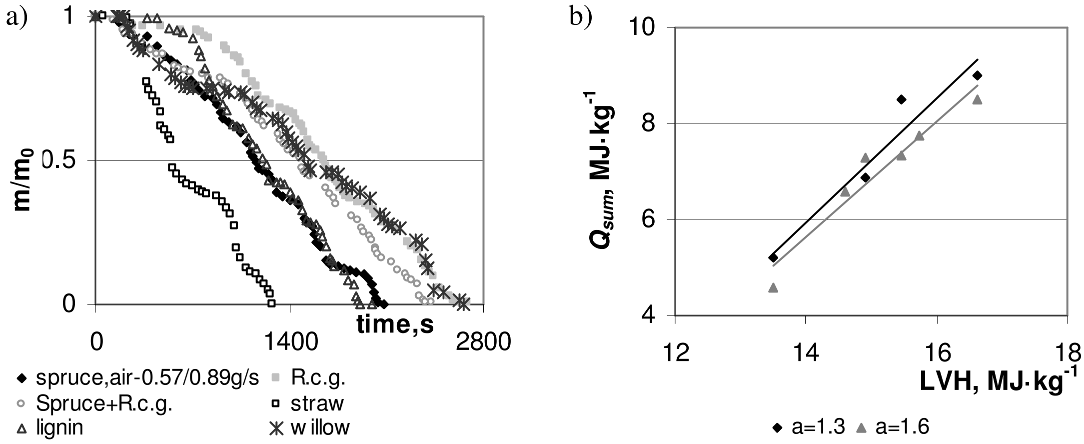

Fig. 1. **Time-dependent variations of the weight loss at thermo-chemical conversion of different biomass samples (a), and correlation between the produced heat energy and LHV (Lower Heating Value) of the biomass pellets at different air excess "a" factors (b)**

The higher carbon content in spruce and wheat straw lignin pellets with the higher biomass heating value (Table 1) results in the correlating increase of the produced heat energy at the thermo-chemical conversion of the pellets (Fig. 1, b). In contrast, the minimum value of the produced heat energy is observed for the wheat straw pellets with the lower heating value and the higher moisture and ash content in pelletized biomass.

The thermo-chemical conversion of the biomass pellets results in time-dependent variations of the composition of products, combustion efficiency and air excess in the products. As follows from Table 3, the highest value of the produced heat energy with the highest average values of the produced volume fraction of CO_2 and the minimum value of O_2 is observed for the spruce pellets and for the pellets of the R.c.g. mixture with spruce sawdust, while the lowest heat energy with the lowest average volume fraction of CO_2 is observed for the wheat straw pellets. An additive of molasses (5 % on dry mass) to willow pellets results in a slight reduction of the produced heat energy decreasing the volume fraction of CO_2 in the products, while allows enhancing of the bulk density of the pellets.

Table 3

Average combustion characteristics of different biomass samples at thermochemical conversion

Characteristics of palletized biomass	Q_{sum}, MJ·kg^{-1}	CO_2, %	O_2, %	CO, ppm	Eff, %	Air excess, %
Spruce sawdust	8.5	10.7	10	120	85	95
Reed canary grass	7.3	9.3	11.5	665	88	151
R.c.g+spruce	7.8	9.6	11.3	140	87	118
Willow	6.9	8.7	12.1	1217	84	161
Willow with molasses	6.6	8.62	12.2	1150	87.5	138
Wheat straw	5.2	8.6	12.2	715	63	147
Wheat straw lignin	8.1	9.4	11.5	130	68	123

The declined burnout of the willow, wheat straw and R.c.g pellets with the correlating increase of air excess in the products provides a relatively large amount of the mass fraction of CO emissions into gaseous products if compared with the combustion characteristics of the spruce sawdust pellets. The reduction of CO emissions can be achieved by decreasing the air excess in the combustion zone to ensure complete combustion of the volatiles and biomass char.

Finally, it should be noted that all biomass samples have quite different nitrogen content in biomass determining different contents of polluting NO_x emission in the products (Fig. 2).

The regression analysis of the correlation between the nitrogen content in biomass and the mass fraction of NO_x emission in the products has shown that this correlation for the above biomass samples can be approximately expressed as a linear dependence $NO_x = f(N)$ with $R^2 \approx 0.95$. Hence, the higher nitrogen content for wheat straw lignin (1.08 %) and wheat straw (0.85 %) pellets leads to the highest average and peak values of the mass fraction of NO_x emission: to 450 ppm for wheat straw lignin and to 273 ppm for wheat straw pellets in the products, while cleaner heat energy with the minimum value of NO_x (up to 75 ppm) emission in the products can be obtained for spruce pellets (Fig. 2).

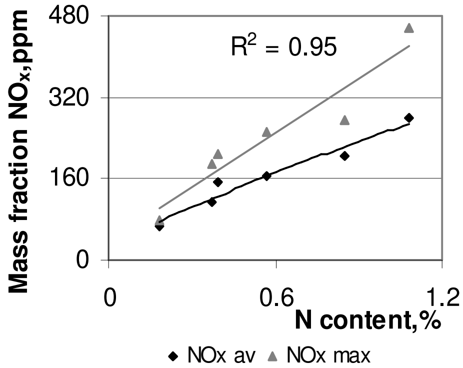

Fig. 2. **Correlation between the nitrogen content in biomass pellets and the mass fraction of NO_x emission in the products**

Conclusions

1. The results obtained testify that pelletized biomass can be utilized as a promising renewable biofuel for cleaner energy production with a pronounced dependence of the processes of thermo-chemical conversion on the chemical and elemental composition of the pelletized biomass.
2. The high content of hemicelluloses and the low lignin content in herbaceous biomass samples and in wheat straw promote high weight loss rates at the gasification stage of thermo-chemical conversion and reduced heat energy production for spruce sawdust samples.
3. The high lignin content in wheat straw lignin samples results in the decrease to the minimum value of the heat energy produced at the gasification stage, and the main heat energy produced at thermo-chemical conversion of wheat straw lignin can be related to char conversion.
4. The higher carbon content in the biomass pellets provides higher heat energy production at thermo-chemical conversion with the higher temperature of the reaction zone and the higher average value of the CO_2 volume fraction in the products.
5. The higher nitrogen content in biomass pellets leads to the correlating increase of the average and peak values (up to 450 ppm) of the mass fraction of NO_x emission in the products.
6. Cleaner and more effective combustion is observed at thermo-chemical conversion of wood biomass.

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