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Effect of Main Characteristics of Pelletized Renewable Energy Resources on Combustion Characteristics and Heat Energy Production

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With the aim to provide a more effective utilization of different renewable energy resources for cleaner and more effective heat energy production, this work presents a complex experimental research and comparison of the chemical composition and combustion characteristics for different types of pelletized biomass fuels. Biomass pellets are produced from wood biomass (spruce sawdust), herbaceous biomass (reed canary grass) and their binary mixtures under previously tested different pelletization regimes. The complex experimental investigation of the main parameters of biomass pellets and their combustion characteristics is carried out along with estimation of correlations between the combustion characteristics and the main characteristics of densified biomass samples. It has been found that the densification of herbaceous biomass with an addition of woody biomass (spruce sawdust) improves the combustion characteristics of the densified herbaceous biomass, providing a faster thermal decomposition of biomass pellets with the increase of the average mass loss rate from 0.125-0.130 g/s for densified reed canary grass to 0.142-0.144 g/s for the mixture of reed canary grass and woody spruce (50:50). The addition of woody biomass ensures a more complete combustion of volatiles and decreases the average mass fraction of polluting emissions (CO, NO_x) in the products. Moreover, the investigation results show that the densified biomass mixture of reed canary grass and spruce sawdust (50:50) has a lower ash content, a higher heating value, an increased heat production rate and total amount of energy in comparison with herbaceous biomass.

1. Introduction

Interest in utilization of biomass fuels as an alternative energy resource of fossil fuels has increased due to the rising prices on fossil fuels and destructive impact of global warming originated from heat and power production. As biomass is considered not to contribute to the greenhouse effect, a wide spectrum of different biomass, including wood and woody biomass (softwood, hardwood, barks, etc.), grasses (reed canary grass, timothy, etc.) as well as straws (wheat, rape, rice straw, etc.) are major renewable energy resources providing up to 15 % of the world's energy needs. Due to the wide variety of biomass resources, significant variations of their physical characteristics, chemical properties and combustion features are observed. Systematic analysis of biomass characteristics has shown (Vassilev et al., 2010) that most of the biomass types have similar contents of C, H and O, while they show significant differences in nitrogen and ash content, depending on plant species, soil types, fertilizers, harvesting time, collection technique and lots of other factors that must be specified (Obernberger and

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Thek, 2004). The main characteristics of different biomass types and their mixtures significantly vary due to the extremely high variations of their structure, moisture content, bulk density and the content of volatile matter, determining specific changes of their heating values with direct influence on the combustion characteristics. Also, different biomass types exhibit differences in their chemical composition – the content of cellulose, hemicelluloses and lignin. For example, the content of cellulose in woody biomass varies within 43.6-47.0 %, the content of hemicelluloses is 25.3-27.1 %, while the content of lignin is 27.7-28.0 % (Sullivan and Ball, 2012). Herbaceous biomass (reed canary grass) shows the higher content of cellulose (42.6-49.2 %) and hemicelluloses (27.9-39.1 %) with the reduced content of lignin 7.6-11.7 % (Vassilev et al., 2012). As a consequence, different biomass types show wide variations in content of volatiles and char as a result of thermal impact in the oxidative atmosphere. The average content of the volatile matter for wood and woody biomass varies as 69.5-86.3 %, for agriculture straws as 64.3–80.5 %, while for herbaceous biomass it lies in the range of 73.4-81.6 % (d.b) (Vassilev et al., 2010). Hence, because of the wide variations of the biomass physical and chemical properties, the combustion characteristics of different biomass types are quite unpredictable. Stabilization of the biomass combustion characteristics, which meet industrial product specifications (Nussbaumer, 2008), can be achieved providing pre-treatment of biomass, i.e. biomass drying and densification (briquetting, pelletization). The subject of this study is to investigate the pre-treatment of three different biomass types - wood biomass (spruce sawdust), herbaceous biomass (reed canary grass) and their binary mixture (50:50) in order to estimate the influence of the variations of the main characteristics of pelletized biomass on the processes of biomass combustion.

2. Experimental setup and procedures

This study comprises a complex research of pelletization regimes, physical and chemical properties as well as combustion characteristics of the densified biomass pellets under nearly stoichiometric combustion conditions.

2.1 Biomass granulation, pelletization and main characteristics of produced pellets

The experimental study of the combustion characteristics for different biomass types (woody biomass, herbaceous biomass and their mixture) starts with the biomass granulation and densification in order to improve and stabilize the biomass characteristics and convert the biomass into a biofuel with certain elemental composition, calorific value, moisture and ash content. To produce a biofuel with controllable combustion characteristics, in the current paper, we discuss the granulation and densification of woody biomass (spruce), herbaceous biomass (reed canary grass - Bamse) and their 50:50 mixture. Typical herbaceous biomass samples show higher nitrogen and ash content and a lower calorific value if compared with woody biomass. Therefore, it is suggested that the mixing of herbaceous and wood biomass improves the combustion characteristics of the herbaceous biofuel.

Before granulation of herbaceous biomass, the samples were grinded in a hammer mill AGICO TSF420C with die holes of 2 mm. The average moisture content of the original herbaceous biomass before granulation was ~17 %, while after grinding it reduced to 10.3 %. The granulation leads to the decrease of the moisture content in reed canary grass (R.c.g.) to 7.1 %. Spruce sawdust with a water content of 50 % was produced from an industrial sawmill unit. The sawdust fraction (≥ 2.0 mm) was dried at 80 ^{o}C up to 11.8 % moisture before granulation. Granulation promotes the reduction of the moisture content in wood biomass to 8.1 %. The granulated herbaceous and woody biomass was mixed using a mixer HTL 30. The following granulation decreased the water content in the binary biomass mixture from 10.9 to 8.2 %. Because of the low moisture content in original reed canary grass, the high energy expensive drying step was excluded from the pre-treatment scheme prior to the granulation of this biomass. It can be considered as one of the reasons of herbaceous biomass applications for the densified fuel production. The biomass was granulated using a flat die laboratory press KAHL 14-175. The main characteristics of the produced biofuel pellets were determined using the methods described in (Arshanitsa et al., 2008).

2.2 Pilot device for the combustion of pelletized biofuels

The kinetic study of the combustion characteristics of pelletized biofuel was carried out using a pilot-size device composed of a gasifier, a combustor and three water-cooled sections separated by

diagnostic sections for local measurements of the flame temperature and composition (Barmina et al., 2008). A layer of batch-sized biofuel pellets (m = 230-300 g) as high as 120-130 mm was placed on a steel grate located at the bottom of the gasifier with 60 mm in diameter. Thermo-chemical conversion of the densified biofuel was initiated in the upper part of the biomass layer using the propane flame flow as an external heat energy source with the average heat energy supply rate 1.2 kJ/s. Primary air supply below the layer of biofuel pellets at the average rate 0.6 g/s is used to support the biomass gasification developing at the average air excess ratio $\alpha \approx 0.35$-0.45. Secondary swirling air was supplied to the bottom part of the combustor through the tangential air nozzles at the average rate 0.6-1.2 g/s. The mass consumption rate of the biomass pellets (dm/dt) during their thermo-chemical conversion was controlled by a test facility consisting of a moving steel rod equipped with a pointer to measure the change of the biomass layer height during the gasification of the biomass samples.
The measurements of the average mass consumption rate for the pelletized biomass samples were used to estimate the air-to-fuel supply rate, which must be provided to achieve the near-stoichiometric combustion conditions in the flame reaction zone. It should be noted that at different stages of thermal degradation of the densified biomass samples, the mass consumption rate rapidly increases with deviation of the air-to-fuel ratio from stoichiometric combustion conditions.The kinetic study of the combustion characteristics includes simultaneous online time-dependent measurements of the temperature in the flame reaction zone, calorimetric measurements of the cooling water flow, combustion efficiency and composition of the main products. Temperature measurements were made using Pt-Pt/Rh thermocouples. Calorimetric measurements of the cooling water flow include the measurements of the water flow rate (L/min) and water flow temperature for each section of the combustor, which were made by temperature sensors. The composition of the main products and the combustion efficiency were measured using a gas analyzer Testo 350 XL. The thermocouples and the gas sampling probes were inserted into the flame reaction zone through the orifices in the diagnostic sections between the water-cooled sections of the combustor.

3. Results and discussion.

As follows from Table 1, the highest carbon and hydrogen contents, the highest values of higher (HHV) and lower (LHV) heating values were found for spruce sawdust samples, while the highest nitrogen and ash content were found in the reed canary grass (R.c.g.) samples.

Table 1: The main characteristics of woody and herbaceous pellets and their mixture (50:50) based on proximate and ultimate analyses.

Characteristics	Spruce sawdust	Reed canary grass (Bamse)	Reed canary grass + spruce sawdust
[1]C,%	49.10	46.75	47.93
[1]H,%	6.44	6.27	6.34
[1]N,%	0.18	0.57	0.37
[1]Ash,%	0.37	3.39	1.88
[2]Moisture,%	8.10	7.10	8.20
[2]HHV, MJ/kg	18.17	16.99	17.51
[2]LHV, MJ/kg	16.63	15.47	15.73
A/F ratio	5.97	5.85	5.90
Diameter, mm	6.06±0.04	6.04±0.03	6.07±0.06
Length, mm	16.7±2.5	18.7±3	16.5±3.4
Bulk density of dispersed biomass, kg/m^3	178±12	145±12	196±6
Bulk density of pellets, kg/m^3	660±10	683±13	669±12
[2]Volumetric energy density, MWh/m^3	3.05	2.94	2.92
Durability, %	95.60	96.50	97.20

[1]- dry samples (d.b)
[2]- as received samples (a.r)

The mixture of R.c.g. with spruce sawdust results in an increase of the carbon and hydrogen content in the pellets, with the correlating increase of the HHV and LHV relative to the reed canary samples, while the nitrogen and ash content decreases, so improving the combustion characteristics of the mixture relative to herbaceous biomass pellets. The growth of the R.c.g pellets bulk density, if compared to dispersed biomass, was the most expressed (4.7 times increase) and the bulk density of the pellets was the highest. But the durability value of the mixed pellets was much higher. Because of the highest bulk density of the reed canary pellets, their volumetric energy density was as for mixed pellets (with a higher LHV) and decreased to 4.5 % of relatively spruce pellets.
The experimental study of the thermo-chemical conversion of the densified biomass samples (spruce, reed canary grass) and their mixture starts with the kinetic study of the mass loss for the pelletized biofuel samples at different stages of biomass gasification. The results were obtained with the fixed primary air supply rate into the gasifier (0.6 g/s) and the fixed rate of additional heat energy supply into the biomass (1.2 kJ/s). The higher rate of the average mass loss (0.153-0.158 g/s) is registered for the densified spruce biomass, while the minimum of the mass loss rate shows the densified reed canary grass (0.125-0.130 g/s). With an addition of spruce sawdust to the herbaceous (R.c.g.) biomass (50:50), the thermal degradation rate increases to 0.142-0.144 g/s (Figure 1).

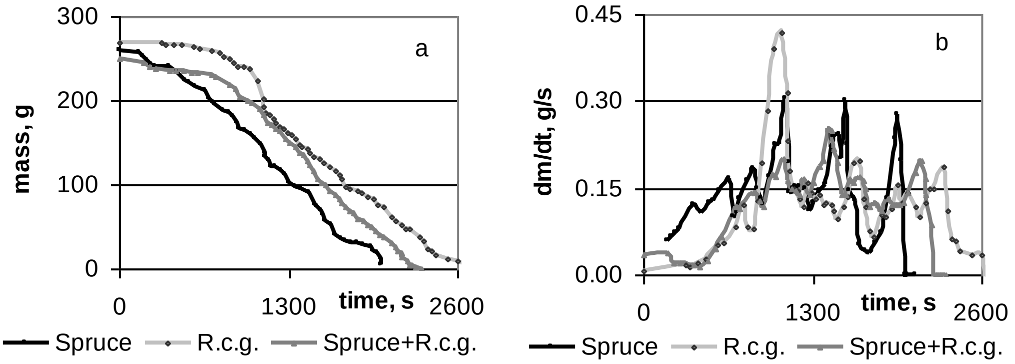

Figure 1: Time dependent variations of the mass loss (a) and mass loss rates (b) for different types of densified biofuels at the primary air supply rate 0.6 g/s.

The time-dependent measurements of the thermal degradation rates of the biomass samples (dm/dt) show (Figure 1-b) the formation of pronounced peaks of the mass loss rates at the primary stage of the biomass pellets thermal degradation (t = 1000-1100 s), which is attributed to the intensive release of volatiles during the biomass gasification (Figure 2-a). As follows from Figure 1-b and Figure 2-a, the most intensive formation of the volatiles is observed for the densified R.c.g. biomass samples when the mass loss rate at the primary stage of thermal degradation (t ≈ 1050 s) comes up to 0.4 g/s, while the mass fraction of CO in the products increases to 4000 ppm (Figure 2-a). The rapid increase of the CO mass fraction at this stage of thermal degradation of R.c.g. evidences the formation of the fuel-rich conditions in the flame reaction zone promoting the correlating decrease of the heat production rate (Figure 2-b). The combustion conditions in the flame reaction zone at this stage of R.c.g. thermal degradation can be improved by increasing the secondary air supply rate into the combustor. The formation of less pronounced peaks of the mass loss rate is observed at the final stage of char conversion (t = 2000-2600 s), when the endothermic reactions of CO and H_2 formation result in a enhanced increase of the mass fraction of CO and H_2 in the products with the correlating decrease of the heat production rate downstream the combustor, the decrease of the volume fraction of CO_2 and temperature of the products (Figure 2).

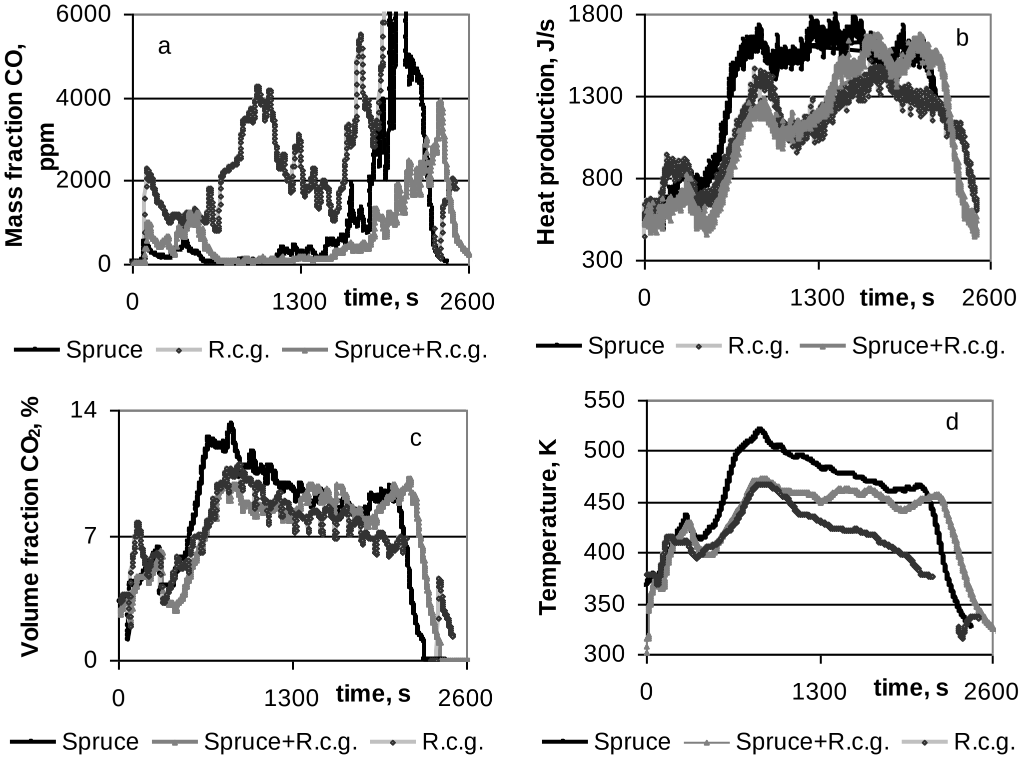

Figure 2: Time-dependent variations of (a) volatiles (CO) formation, (b) rate of heat energy production, (c) main product (CO_2) formation and (d) product temperature at the thermo-chemical conversion of densified biomass under stoichiometric combustion conditions (α ≈ 1) downstream the combustor.

As follows from Figure 2, an addition of spruce sawdust to the herbaceous (R.c.g.) biomass, with the average combustion conditions ($\alpha_{av} \approx 1$) being equal, promotes the stabilization of the combustion characteristics during the burnout of volatiles (t ≈ 1100-2000 s) with a higher rate of heat production. In accordance with data on HHV variations for the produced biomass samples (Table 1), the addition of spruce sawdust to the R.c.g. biomass in the proportion 50:50 results in an increase of HHV from 17.0 to 17.5 MJ/kg, with the correlating increase of heat production downstream the combustor, when the energy production increases from 9.5 MJ/kg for the combustion of R.c.g. to 10.3 MJ/kg for the biomass mixture. The analysis of correlations between the HHV of biomass samples, heat production rate (Q, kJ/s) and the total amount of produced heat (Q_{sum}, MJ/kg) yields a linear increase of the heat production rate and total amount of the produced heat downstream the combustor, with an increase of the HHV with the correlation coefficient $R^2 \approx 1$. Finally, it should be emphasized that the combustion of the mixture of spruce sawdust with R.c.g. results in a reduced level of nitrogen emissions (NO), decreasing the peak and average values of NO_x in the products relative to their values for the R.c.g. pellets (Figure 3).

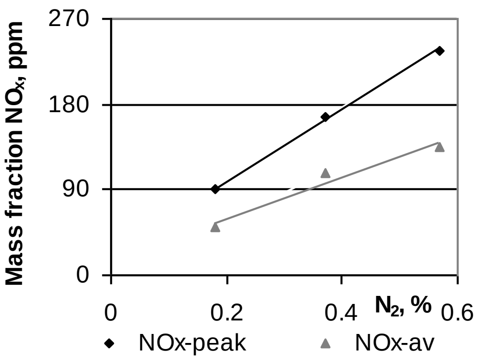

Figure 3: Correlation between the NO_x emissions and the nitrogen content in biomass samples.

4. Summary

In this study, experiments were carried out providing densification of three different types of biomass - spruce sawdust, herbaceous biomass and their mixture (50:50) applicable as fuels. The nitrogen and ash content and the calorific values in the mixed pellets take approximately the middle position in the data on spruce and reed canary grass pellets. The low moisture content in original reed canary grass will decrease the energy consumption for the mixed biomass drying before granulation in contrast to that of pure spruce sawdust.

The complex research on the biomass and combustion characteristics show the direct correlation between the variations of the heating value of the biomass samples, heat production rates and the total heat amount produced downstream of the combustor. An addition of spruce sawdust to the biomass of reed canary grass allows improving the combustion characteristics with the increase of the heat production and promotes the reduction of the mass fraction of polluting NO_x emissions in the products.

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