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Processing and Complex Research of the Main Characteristics of Pelletized Lignocellulosic Materials for Clean and Effective Energy Production

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Abstract

The paper presents results of complex experimental study of the composition and heating values as well as the combustion and emission characteristics of a pelletized biomass fuel produced from softwood and wheat straw non-hydrolyzed lignocellulosic residues (LHRs) of bioethanol production. Those biofuels can be estimated as prospective alternative renewable energy sources for clean heat and energy production by direct combustion or gasification. A small-scale pilot combustion system with swirl-stabilized flame of volatiles and heat power output up to 3 kWh was used in experiments. The results of local time-dependent measurements of the flame temperature, heat production rates and emission characteristics of LHR granules are compared with those of commercial softwood granules. The gasification step of LHRs granules results in an enhanced release of CO and free hydrogen emissions in comparison with the gasification step of softwood granules. This predetermines the possibility of LHRs granules use for syngas production. It is found that the high content of nitrogen in the LHR granules results in a relative high mass fraction of NO_x emissions in the products. Less impact of the LHR combustion on the environment with a higher heat output can be achieved by co-firing the LHR with softwood granules.

Introduction

The limited availability of fossil fuels and the necessity of environment protection from greenhouses gas emissions promote an intensive research and development of alternative energy sources for the clean and effective energy production [1, 2]. Biomass is the third largest primary energy resource in the world, and it is estimated to be more than 10% of the total word energy consumption [3]. Up to now, the low energy density, dissimilar structure and high moisture content of different types of biomass restrict its utilization for the clean and effective energy production. Granulation is a recognized way to enhance the efficiency of plant biofuel utilization for energy production by increasing its energetic density with simplification of biomass transportation, storage and automation of fuel supply systems. Softwood pellets are the most widespread type of granulated biofuel. Because of the intensive utilization of wood biomass for energy production during the last few years, the good quality saw dust and wood chips become less available. Non-hydrolyzed lignocellulosic residues (LHRs) of bioethanol production can be considered as an alternative material for the granulated biofuel production. About 40-60% of LHRs must be incinerated in plant boilers. The remaining LHRs can be utilized as a granulated biofuel that allows to obtain additionally ~0.6 MW and ~2.0 MW of heat per 1 MW of ethanol energy in case of softwood and wheat straw hydrolysis, correspondingly [4]. The application of granulated LHRs for heat energy production will make a valuable contribution to the process economy, decreasing the total cost of the bioethanol production. Moreover, gasification of lignocellulosic residues with a high carbon and hydrogen content can be used to produce a syngas for heat and electricity generation. Large-scale biomass gasification plants in Austria, Great Britain, Sweden, etc. allow a more effective and low cost utilization of different types of biomass [5-9].

The previous study of the combustion and emission characteristics of LHRs granules produced from spruce wood by dilute acid hydrolysis and enzymatic hydrolysis has shown that the combustion of LHRs pellets produced by a screw extrusion technology is characterized by a higher rate of heat production and a faster ignition of the volatiles with an enhanced release of CO_2, NO_x and SO_2 in comparison with the softwood granules [10]. The main disadvantages of the LHRs granules produced by the screw extrusion technology are the lower bulk density values (450-550 kg/m^3) if compared to commercial softwood granules (650-700 kg/m^3) that decreases the energy density of the biofuel. The aim of the present study is the investigation of the combustion process including the gasification step of softwood LHRs and LHR wheat straw granules with a high bulk density of 720-730 kg/m^3. The increasing density of the LHRs granules up to the values of commercial softwood granules was achieved using a pellet mill technology for granulation instead of screw extrusion. To reduce the NO_x emission as well as the bottom ash content, co-firing of renewable LHR granules with softwood granules was investigated.

1. Experimental

1.1. Materials and Method of Investigation

Non–hydrolyzed residues of softwood 3/4 were manufactured at the Ornskoldsvik pilot plant (Sweden) by enzymatic hydrolysis of softwood with simultaneous saccharification and fermentation. Non–hydrolyzed residues of wheat straw 1142 were manufactured at the SAFISIS pilot plant (France) by enzymatic hydrolysis of wheat straw with separated saccharification and fermentation stages.

The LHRs were pelletized using a laboratory pellet mill KAHL 14-175. The water and ash content in the granulated LHRs were determined according to CEN/TS 14774-1 and CEN/TS 14775, correspondingly. Klason lignin (KL) was determined according to [10]. C, N H, S in total were determined using the Analysis System Vario Macro CHNS. Higher heating values (HHV) and combustion sulphur content (S_{comb}) were found according to ISO1928 and CEN/TS 15289. Bulk densities of the granules were determined according to CEN/TS 15103. The mechanical durability (DU) values of the granules were determined in accordance with CEN/TS 15210-1 (Tab. 1-2).

Commercial softwood granules were used for references.

Tab. 1: Composition and heating values of origin softwood and LHRs on dry mass

Biomass granules	HHV, kWh/kg	Klason lignin content , %	Elemental content, %					
			C	H	N	S_{tot}	S_{comb}	Ash
Softwood	5.4	28.8	50.2	6.3	0.24	0.13	0.02	0.60
LHR softwood 3/4	6.2	51.5	55.2	4.8	0.43	0.32	0.15	0.40
LHR wheat straw 1142	5.4	44.4	49.7	5.3	1.1	0.35	0.11	6.4

Tab. 2: The main characteristics of the LHRs and commercial softwood granules

Sample	Water content,%	LHV, kWh/kg	Bulk density, kg/m^3	Energy density, MW*h/m^3	DU,%
LHR softwood 3/4	7.6	5.4	735	4.0	97.7
LHR wheat straw 1142	9.2	4.6	720	3.3	98.8
softwood	7.2	4.7	699	3.3	98.6

1.2. Combustion System

The combustion process of different types of biomass granules was studied experimentally using a compact experimental setup with the total heat output up to 3.0 kWh (Fig.1). The setup consists of a wood biomass gasifier (1) charged with biomass (230-260 g), a premixed swirling propane/air burner, which provides an additional heat supply into the gasifier (2), and a sectioned water-cooled channel (5). The primary (3) and secondary (4) airflows were used to initiate the biomass gasification and provide a complete burnout of volatiles. The primary airflow was injected into the bottom part of the gasifier at the rate 46 l/min. The secondary swirling airflow was supplied into the upper part of the gasifier at the rate 71 l/min.

The diagnostic sections with orifices (6) were used to insert the diagnostic tools (thermocouples, gas sampling probes) into the flame of volatiles. The local flame temperature was measured by Pt/Pt-Rh (10%) thermocouples with a PC-20TR computer system for data collecting and recording. From the calorimetric measurements of the cooling water flow the average heat production rate was estimated for different stages of the burnout of volatiles. The temperature and composition of the products (T, NO_x, CO_2, CO, H_2, O_2) were on-line registered at the channel outlet using a Testo 350XL gas analyzer.

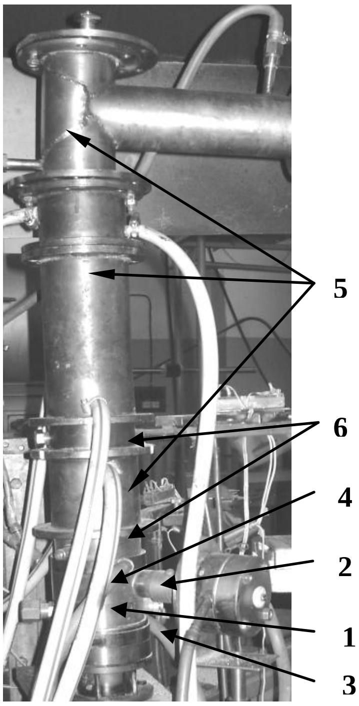


Fig. 1. The digital image of the small-scale experimental device

2. Results and Discussions

The self-sustaining combustion of biomass includes the following main steps: water evaporation, biomass gasification resulting in the formation of carbohydrates and thermal degradation of lignin producing volatiles, ignition and combustion of the volatiles and char combustion. The most intensive water evaporation from the biomass occurs at T ≈ 370 K. Then follows thermal decomposition of hemicelluloses at T ≈ 470-570 K, of cellulose at T ≈ 520-630 K and of lignin at T ≈ 450-770 K. The main products of the biomass gasification are: CO, H_2, CH_4, CO_2, H_2O, N_2, gaseous olefins, aromatics, primary and secondary condensed oils and charcoal [8, 9]. The simplified reaction of the biomass gasification at about 10% water content (hydrothermal gasification) can be expressed as:

$$\text{Carbohydrate matter } (C_6H_{10}O_5) + 6O_2 + mH_2O + \text{Heat} \rightarrow 6CO + 5H_2 + nH_2O \quad (2.1)$$

The results of the experimental study have shown that for the given main characteristics of the LHRs and commercial softwood (Tab. 2) at constant rates of primary and secondary air supply in the combustor, the process of granulated LHR gasification ($t < 500$ s) results in an intensive formation of a mixture of the combustible volatiles CO and H_2 (Fig. 2) with approximately constant ratio of $H_2/CO \approx 0{,}66$ during the gasification of the different biomass types. Higher contents of CO and H_2 in the products are observed during the gasification of the lignocellulosic residues (LHR softwood 3/4 and LHR wheat straw 1142) with a higher Klason lignin content in comparison with the softwood (Fig.2, Tab. 1) that is important for the syngas production by the LHRs granules gasification.

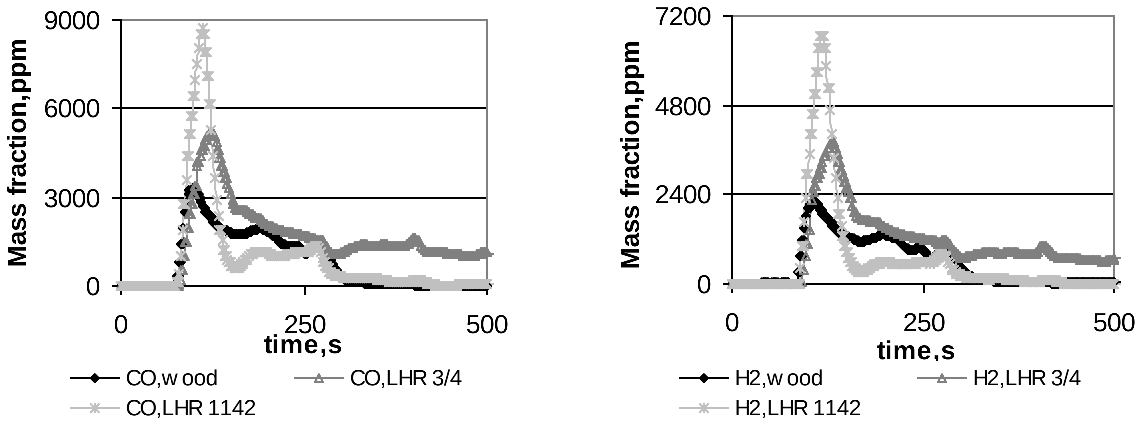
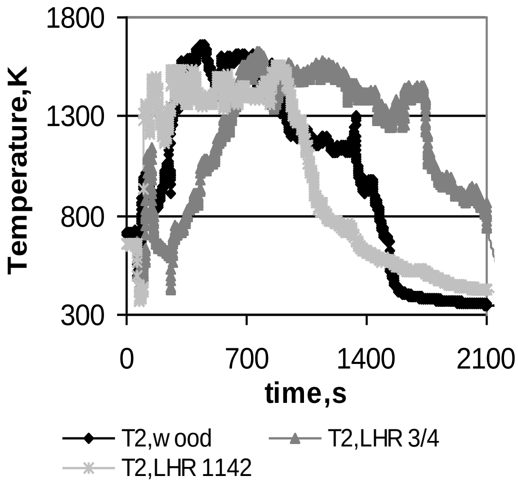


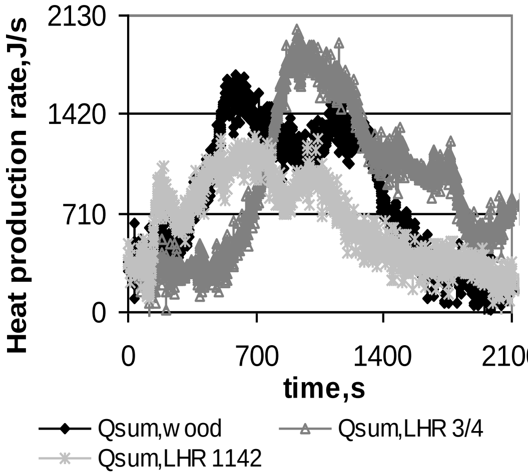
Fig. 2. Time dependent variations of the mass fraction of CO and H_2 at the gasification stage of different types of granulated biomass fuel ($t < 500$ s)

At the next stage of the biomass combustion ($t > 500$ s), the ignition and burnout of the volatiles results in a fast increase of the temperature up to 1600-1700 K with a correlating increase of the heat production rates and CO_2 volume fraction in the products, while the mass fraction of CO in the products decreases to a minimum value (50-150 ppm) (Figs. 2, 3). The simplified reaction of the biomass combustion can be written as:

$$\text{Carbohydrate matter } (C_6H_{10}O_5) + 6O_2 + (m-n)H_2O \rightarrow 6CO_2 + (5+m-n)H_2O + \text{Heat} \quad (2.2)$$

As one can see from Tab. 1-2 and Fig.3, the higher content of carbon and the higher heating value of the LHR softwood granules result in a higher amount of the total heat production (7.7 MJ/kg) if compared to that of softwood (7.1 MJ/kg) and LHR wheat straw (5.4 MJ/kg). The lower heat output is observed for the LHRs wheat straw, which can be explained by the prolonged char combustion at the end stage of the wheat straw burnout in the bottom part of the gasifier that is not equipped with a water-cooled jacket determining the reduced amount of the produced heat energy. These features of the LHRs wheat straw must be accounted for when develop a large-scale boiler for the combustion of granulated LHRs.





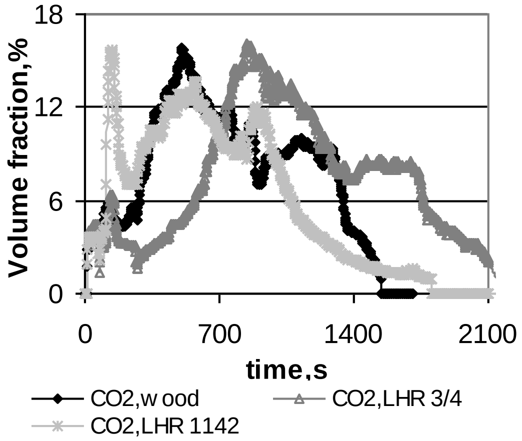


Fig. 3. Time dependent variations of the flame temperature, heat production rate and volume fraction of CO_2 in the products at different stages of the biomass combustion.

The higher mass fraction of NO_x in the products (up to 500 ppm) is observed for the burnout of the LHR wheat straw with a higher content of nitrogen in granulated biomass (Tab. 1, Fig. 4). For the softwood granules, the mass fraction of NO_x in the products decreases to 100 ppm. The more effective utilization of non–hydrolyzed residues with a higher heat energy production (up to 8 MJ/kg for the LHR softwood and 6.4 MJ/kg for the LHR wheat straw) and the reduced total amount of NO_x emission by 27% for the LHR softwood and by 25% for the LHR wheat straw were observed at co-firing the LHR with softwood granules at the mass ratio of LHR and softwood equal to1.0 (Fig. 4).

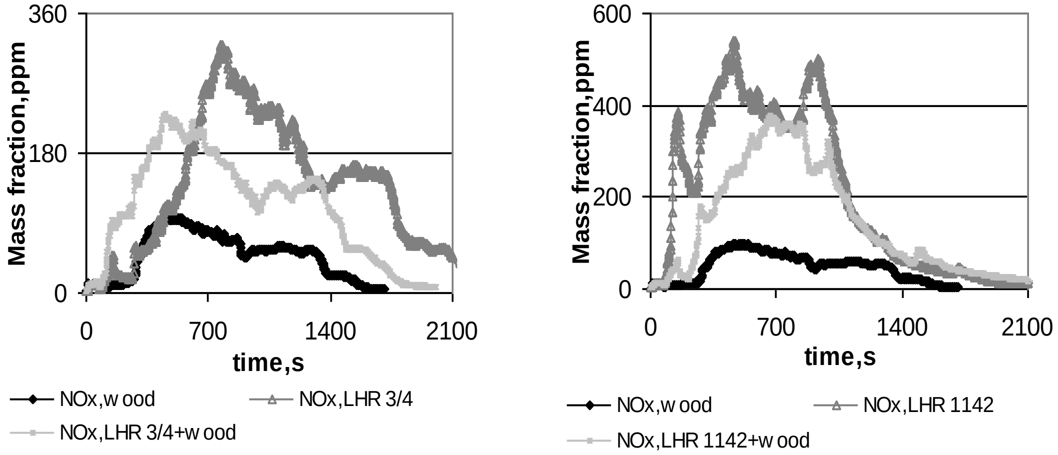


Fig. 4. The effect of co-firing the LHRs with softwood granules on the formation of NO_x at different stages of the biomass combustion

Besides, the co-firing of the LHRs wheat straw with softwood granules has resulted in a significant decrease of the total ash content from 6.4 to 3.5 % for dry biomass.

Conclusions

1. The non-hydrolyzed lignocellulosic residues of bioethanol production from wood and wheat straw are new efficient biofuels with higher heating values and higher carbon contents that can be used for the heat energy production by direct combustion.

2. The increased lignin content in the LHRs granules provides the biomass gasification with a higher CO and H_2 mass fractions in comparison with that for softwood granules. This fact allows predicting some potential for the LHRs granules' use as a biofuel in gas-generator facilities for heat and energy production.

3. The LHRs granules (especially from wheat straw) contain a relatively high concentration of nitrogen, sulphur [10] and ash in comparison with softwood granules. For a more efficient utilization of the LHRs granules with a higher heat energy output, a reduced harmful emission and ash content joint LHR and softwood granule combustion can be applied.

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