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Effect of Biomass High-Frequency Pre-Treatment on Combustion Characteristics

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Combustion characteristics of microwave (2.45 GHz) pre-treated biomass (wood) pellets are investigated experimentally with the aim to find out the effect of pellets pre-treatment on the biomass composition and the feasibility of their thermo-chemical conversion. A complex study of the main combustion characteristics of the pre-treated biomass samples was carried out using a thermo-gravimetric method and a pilot–scale combustion test facility. The study includes time dependent measurements of mass loss at the primary stage of biomass gasification, variations of the flame temperature and heat production rate, combustion efficiency and composition of pollutants. The results have shown that the low-temperature microwave pre-treatment of wood pellets enriches the biomass carbon content from 50 % to ~ 60 % (d.b.) for biomass pre-treated for 180 s accompanied by the increasing higher heating values (HHV) from 19.9 up to 23.4 MJ/kg. The microwave pre-treatment promotes a faster thermal decomposition of biomass pellets with an enhanced heat energy production (up to 30 %) and a correlating increase of the volume fraction of CO_2 in the products up to 25-28 %, while the mass fraction of the main volatiles (CO and H_2) in the products decreases, indicating a more complete combustion of the volatiles. The shear of the char combustion stage increases with the increasing pre-treatment time. The data of thermo-gravimetric analysis coincide with the results of the pilot-scale tests.

1. 1. Introduction

Biomass, in particular, different types of wood biomass (softwood, hardwood) has historically been an important renewable energy source for energy production. Variations in chemical composition, structure (logs, chips, sawdust, etc.), moisture content and in energy density diversify the behaviour of wood biomass during its thermo-chemical conversion (gasification, combustion) thus limiting its range of application. There is a marked need for transition to a more predictable energy production. It can be achieved providing biomass densification (pelletization, briquetting), as well as thermal preprocessing of biomass at temperatures of 500-700 K, producing a solid product of torrefied wood with an improved heating value and low moisture content (Bergman et al., 2004). The microwave pre-treatment can be used (Lanigan et al., 2008; Lanigan, 2010) as an alternative approach to the conventional thermal preprocessing of biomass. The complex research of biomass pre-treatment has shown (Prins, 2005; Lanigan, 2010) that transition to a more predictable biofuel is closely linked to the effect of microwave pre-treatment on the chemical composition of biomass. The investigation of microwave-assisted pre-

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treatment of lignocellulosic biomass has shown that microwave pre-treatment provides enhanced moisture vaporization from the biomass depths, enhanced volatilization of low-calorific organic gases determining increased porosity of biomass (Lanigan, 2010; Sobhy and Chaouki, 2010). At microwave pre-treatment cellulose and hemicelluloses undergo structural changes and, as a result, a biomass with higher energy value and cleaner energy production is produced (Lanigan et al., 2008). The mechanism of microwave pre-treatment effect on biomass has been widely discussed, however, it is agreed that the microwave pre-treatment technology offers a more efficient method of biomass heating, promotes new reaction pathways and accelerates reaction rates as a result of non-thermal effects. The subject of this study is to provide the microwave pre-treatment of wood pellets along with estimation of the impact of the microwave pre-treatment on the thermal decomposition, combustion characteristics and heat energy production during the burnout of pre-treated wood biofuel. Actually, this research comprises a complex study of the effect of microwave pre-treatment regimes on the thermal decomposition as well as on the combustion characteristics of densified products under nearly stoichiometric combustion conditions of pelletized wood biofuel samples. Correlations between the combustion characteristics of pre-treated biomass, pre-treatment time and energy are studied and analyzed to obtain the optimal pre-treatment regime and combustion conditions of pre-treated wood biomass pellets.

2. 2. Experimental setup and procedures

The effect of microwave pre-treatment on combustion characteristics is analyzed at different durations of microwave pre-treatment in a microwave oven along with estimation of the biomass mass loss at different pre-treatment regimes.

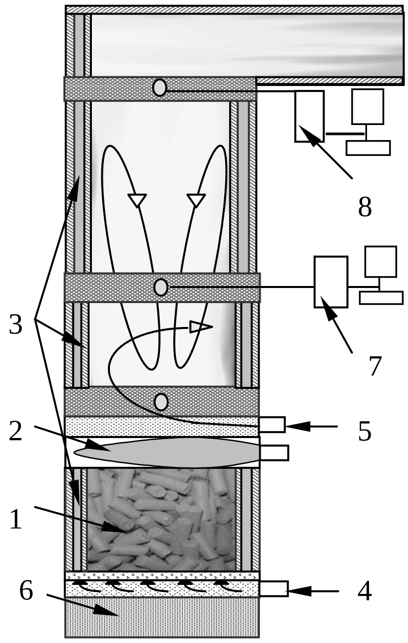

Figure 1: Principal schematic drawing of the experimental set-up: 1 - gasifier, charged with biomass pellets; 2 – additional heat energy supply from propane flame flow; 3 - water-cooled sections of the gasifier and the combustor; 4 – primary air supply; 5 - secondary air supply, 6 - ash collection vessel; 7 - flame temperature online measurements; 8 - online measurements of the combustion efficiency and composition of the products.

Elemental compositions of the pre-treated biomass, ash and moisture contents were determined in accordance with EN 15104:2010, EN 14775:2009 and TS 14774-1:2011 standards, correspondingly. Higher heating values (HHV) were calculated by taking into account the elemental composition of the biomass (Friedl et al., 2005). Combustion tests of the pre-treated biomass were performed applying a thermo-gravimetric method (TG) of high sensitivity and a pilot-size combustion device. The TG investigations were realized for samples grinded in a ball Mixer mill MM 200 and dried in an oven using the Mettler Toledo Star System TOA/SDTA 851 at a heating rate of 10 K/min, air flow rate of 50 mL/min and sample mass of 8 mg. The biomass samples were thermo-gravimetrically analyzed in order to estimate the microwave pre-treatment effect on the variations of biomass composition.

The pilot-scale combustion device used to study combustion characteristics is composed of a gasifier and a combustor (Figure 1). A layer of batch-sized biofuel pellets (m = 230-300 g) of an average height of 120-130 mm was placed on a steel grate located at the bottom of the gasifier of 60 mm in diameter. Thermo-chemical conversion of the densified biofuel was initiated in the upper part of the biomass layer by the propane flame flow with the average heat energy supply rate 1.2 kJ/s.

Primary air is supplied below the biofuel pellet layer at an average rate of 20-30 L/min to support the biomass gasification, which develops 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 supply rate 30-60 L/min providing the complete combustion of volatiles downstream the combustor.
The mass consumption rate of wood pellets (dm/dt) during their thermo-chemical conversion was controlled by a test facility consisting of a moving steel rod equipped with a pointer that allowed measurements of the biomass height variations during the gasification of biomass samples. The measurements of the average mass consumption rate of 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.
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 made by temperature sensors include measurements of the water flow rate (L/min) and water flow temperature for each section of the combustor. The composition of the main products and the combustion efficiency at different stages of the flame formation was measured by 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 placed between the water-cooled sections of the combustor.

3. Results and discussion

Under the investigated conditions, the pre-treatment time is strongly influenced by the composition of wood biomass (Table 1).

Table 1: The characteristics of initial and pre-treated wood.

Pre-treatment time, s	Elemental composition (d.b.), %				Moisture, %	Ash (d.b.), %	HHV (d.b), MJ/kg
	C	H	N	O*			
0	50.0	6.08	0.15	41.7	8.9	2.1	19.9
60	50.0	6.11	0.13	41.2	2.6	2.2	19.9
120	54.9	5.60	0.14	36.2	2.1	3.2	21.9
180	59.9	5.15	0.13	31.0	2.2	3.8	23.4

*-by difference

The drying process was not practically accompanied by the destruction of the wood lignocarbohydrate complex, and the short (60 s) pre-treatment resulted in the evaporation of absorbed moisture. The increase of the pre-treatment time to 120-180 s significantly affected the wood composition by increasing the proportion of carbon. The increase of the carbon content in biomass at a longer pre-treatment is explained by the elimination of volatiles produced as a result of the most thermo-labile carbohydrate degradation (Gani and Naruse, 2007). The difference between energy and mass calculated values clearly testifies that the volatized products evolved as a result of the microwave impact are enriched in oxygen and have low energetic density, and the higher heating values (HHV) of the pre-treated biomass exceeds that of untreated wood by 9-15 %. The growth of the ash content in the microwave pre-treated biomass (as a result of concentration effect) can be assumed as a negative factor from the fuel characteristics point of view. The partial thermo-destruction of carbohydrates as a result of microwave treatment adds to the lignin content in the pre-treated wood if compared with untreated samples. Therefore, different time dependencies of the mass loss and heat loss for pre-treated and untreated samples can be expected.
The experimental study of the effect of biomass pre-treatment on the biomass combustion characteristics in the pilot-scale device starts with the measurements of the biomass mass loss during the microwave pre-treatment by increasing the pre-treatment duration to 300 s, when the mass loss of the pre-treated samples achieves 18-20 %. After the microwave pre-treatment, the pre-treated samples were subjected to gasification and combustion under nearly constant gasification ($\alpha \approx 0.35$-0.45) and

combustion conditions (α ≈ 1) providing the measurements of time-dependent variations of the mass loss in the pre-treated samples (Figure 2).

As follows from Figure 2, the increasing duration of the microwave pre-treatment results in a faster thermo-chemical degradation decreasing the duration of thermo-chemical conversion from 1,600 s to 1000 s with an intensive release of volatiles during the primary stage of biomass gasification (t < 600 s). The longer microwave pre-treatment results in a gradual decrease of the mass loss peak values for the pre-treated samples from 0.46 g/s to 0.39 g/s. The thermo-gravimetric analysis of the pre-treated samples has confirmed the variations in mass loss rates during the thermo-chemical conversion of these samples, indicating the mass loss decrease at the primary stage of biomass devolatilization at microwave pre-treatment, while the mass loss increases at the char combustion stage (Figure 3). As the process of lignin thermo-destruction is accompanied by a condensation process with a higher char yield and a lower amount of removed volatiles in contrast to the thermo-destruction of cellulose (Gani and Naruse, 2007), the higher lignin content in the biomass leads to the higher mass loss as a result of char combustion.

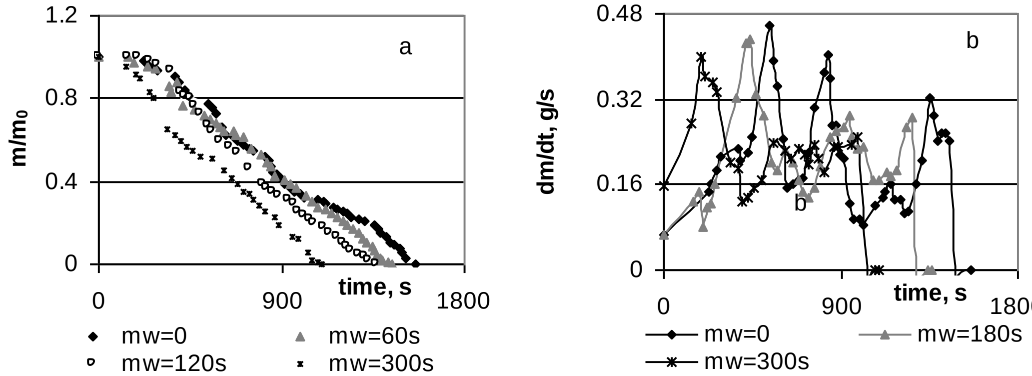

Figure 2: Effect of the microwave pre-treatment duration on the relative mass loss (a) and mass loss rate variations (b) of pre-treated samples at different stages of thermo-chemical conversion.

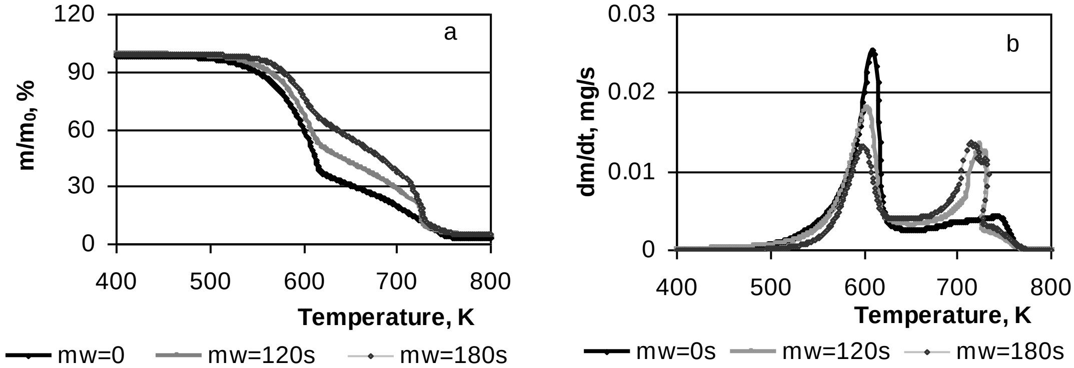

Figure 3: Temperature dependence of the mass loss (a) and rates of the mass loss (b) of untreated and pre-treated wood biomass combustion from the TG analysis.

The mass loss rate decreases with the increased pre-treatment time due to the removal of the most thermo-labile products under the microwave impact. In contrast, the rate of the initial lignin destruction and the rate of the following char combustion of the pre-treated biomass increase significantly if compared with the same processes for untreated wood (Figure 3), thus ensuring the faster total burnout process of the pre-treated samples. The higher rate of the pre-treated biomass char combustion provides a more favorable morphological structure of the pre-treated biomass char for oxygen diffusion due to its higher porosity. In general, the TG results agree with the experiments carried out in the pilot scale device. Some non-conformities can be explained by overlapping of different steps of the biomass combustion in the pilot-scale experiments, while the TG method examines these steps separately. The variations of the thermo-chemical conversion rate of the pre-treated samples initiate variations of the combustion characteristics determining a faster burnout of the volatiles and wood char with a faster increase of the temperature and heat production rates up to their peak values, while the heat energy production rate increases at the primary stage of the thermal conversion of the pre-treated biomass (Figure 4).

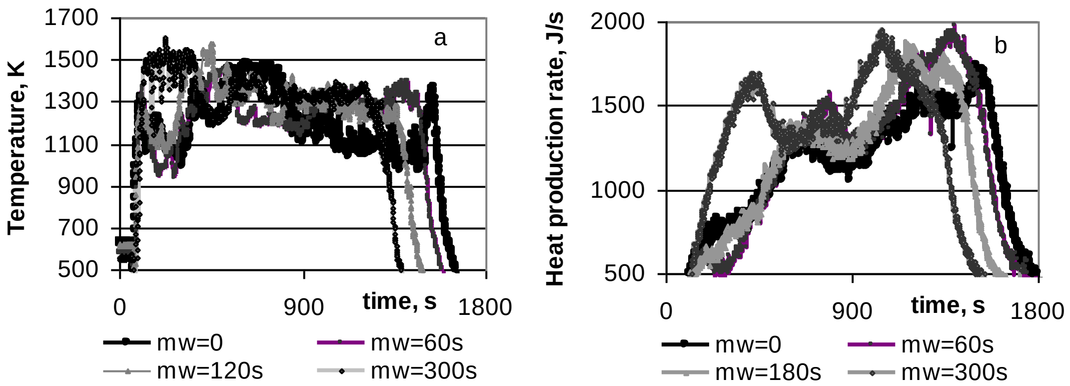

Figure 4: Effect of the microwave pre-treatment duration on the time-dependent variations of temperature (a) and heat production rates (b) at different stages of thermo-chemical conversion.

The variations of the combustion characteristics of the pre-treated samples result in variations of the composition of the products increasing the average value of the volume fraction of CO_2 in the products and the combustion efficiency, so evidencing that the microwave pre-treatment provides a more complete biomass combustion (Figure 5) with a quite negligible effect of the microwave pre-treatment on the mass fraction of NO_x emissions in the products at an almost constant average mass fraction of NO_x in the products – 60 to 61 ppm.

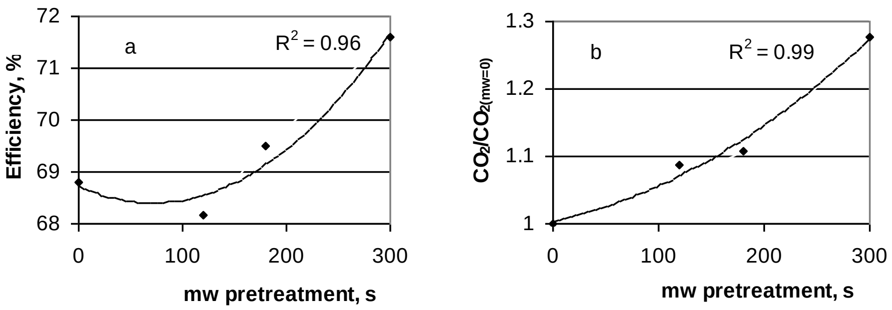

Figure 5: Effect of the microwave pre-treatment duration on the variations of combustion efficiency (a) and CO_2 volume fraction (b).

It should be noted that a similar effect of the microwave pre-treatment on the combustion characteristics was observed when investigating processes developing in a micro-furnace at the average time of microwave pre-treatment of wood pellets 90 s, which showed an increase of the volume fraction of CO_2 in the products by about 8-9 %, while the average volume of produced heat can be increased up to 29 %.

4. Summary

The complex study is carried out to evaluate the effect of microwave pre-treatment regimes on the thermal decomposition of wood biomass as well as on the combustion characteristics of wood pellets under nearly stoichiometric combustion conditions.

The influence of the microwave pre-treatment on wood pellets increases with the increasing pre-treatment time. The short time (60 s) of the microwave impact leads to the drying of wood pellets without significant influence on the composition of the lignocarbohydrate complex. The longer microwave pre-treatment (180-300 s) leads to the removal of low-calorific volatiles and to the carbon content increase thus increasing the heating value (HHV) of pre-treated biomass samples. According to the TG data the increased duration of the microwave pre-treatment lead to the increased shear of the char combustion step of the wood biomass pellets.

The microwave pre-treatment provides more complete biomass combustion as the combustion process of the pre-treated samples has higher average value of the volume fraction of CO_2 in the products and higher combustion efficiency.

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