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Combustion Dynamics of Biomass Mixtures with Microwave Pre-Processing of Pellets

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Abstract

Combustion dynamics of wheat straw mixtures with wood or with peat pellets is studied experimentally with the aim to provide a more effective application of wheat straw for heat energy production. Microwave pre-processing of pellets is used to activate their thermal decomposition and thus enhance the release and thermo-chemical conversion of combustible volatiles. Results of the complex measurements of the main flame characteristics and composition of the products show that the enhanced thermal decomposition of pellets provides improvement of the combustion conditions in the flame reaction zone completing thus the combustion of volatiles, increasing the flame temperature, the heat output from the device and energy efficiency and decreasing at the same time the mass fraction of unburned volatiles in the products.

Introduction

The EU Energy Policy Strategy, which complies with the Kyoto Protocol, prescribes the increased use of cleaner renewable energy sources, partially replacing the fossil fuels with the second generation fuel – wood and agriculture residues [1]. Growing demand for application of agriculture residues for energy production stimulates the production of different types of straw pellets (rape, rice, wheat), which have been known as a more problematic fuel if compared with wood because of the lower heating values (LHV, HHV), higher nitrogen and ash contents in biomass. For that reason, there is a necessity to improve the main combustion characteristics and composition of emission [2, 3]. In order to ensure the wider use of straw for energy production, the co-combustion of straw with renewable or fossil fuels may be used to reduce greenhouse gas emissions during the heat energy production and to improve the main combustion characteristics and the composition of emissions [4]. Further improvement of the combustion characteristics and composition of emissions if straw is used as a fuel, can be achieved using microwave (mw) pre-processed straw pellets that reduces the content of physically bounded water and partially decomposes hemicelluloses, cellulose and lignin, thus reducing the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) content in biomass pellets while increasing their calorific value [5-7]. Actually, it has been demonstrated that mw-pretreatment is an interesting and efficient alternative for biomass conversion to high quality biofuels [8-10].

The results of previous research showed that the microwave pretreatment of biomass pellets could enhance the thermal decomposition of biomass pellets with a faster and more complete thermo-chemical conversion. The main aim of the current study is to provide a more efficient use of wheat straw for energy production by co-combusting straw with wood or with peat pellets and assuring in this way additional improvement of the energy properties of straw pellets at their mw pre-processing. The influence of mw pre-processing of straw pellets on the development of combustion dynamics at thermo-chemical conversion of the activated straw mixture with wood or with peat pellets is estimated and analyzed.

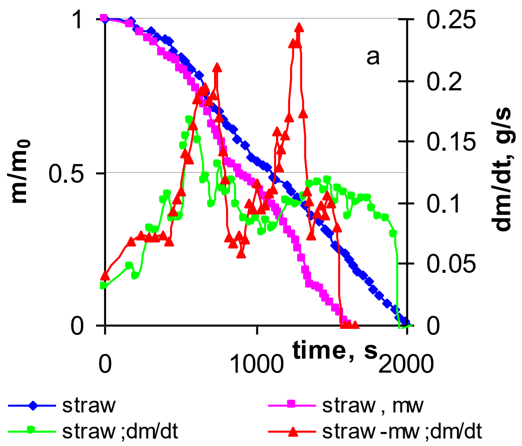
1. Experimental

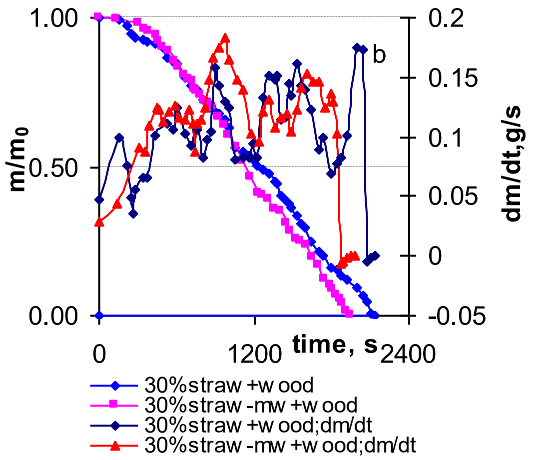
The effects of mw pre-processing of the mixture components (wheat straw mixtures with wood or with peat pellets) on the gasification/combustion characteristics were studied using a pilot device with a heat output up to 2 kW, which combines a biomass gasifier filled with biomass pellets and the water-cooled sections of the combustor [4]. The experiments were carried out using mixtures of straw with wood or with peat pellets, where the straw mass load in the mixture was 30%. To provide activation of the straw thermal decomposition, the straw pellets were pre-processed in a microwave oven at the frequency $\nu = 2.45$ GHz during $t = 180$ s on the average. The gasification/combustion characteristics were studied experimentally with the primary air (q_1) supplied below the biomass layer at the average rate $q_1 = 20$ l/min to sustain the thermal decomposition of the biomass mixture and the formation of combustible the volatiles (CO, H_2). The secondary swirling air flow was supplied at the bottom of the combustor at the average rate $q_2 = 30$ l/min to sustain the burnout of the volatiles downstream the combustor. A propane flame flow was supplied into the upper part of the biomass layer to initiate the thermal decomposition of the biomass pellets and it was turned off after the ignition of the volatiles ($t = 360$ s). To assess the influence of the straw pre-processing on the development of the main gasification/combustion characteristics at thermo-chemical conversion of activated mixtures, the experimental study involved complex time-dependent measurements of the mixture weight loss as well as of the composition of released volatiles entering the combustor, the flame temperature, the heat output from the device and the composition of the products. The FTIR spectrum analysis in the mid-IR range assisted in measuring the composition of the volatiles entering the combustor. Pt-Pt/Rh thermocouples were used to measure the flame temperature with data online registration by a Pico logger. To revalue the influence of the straw pre-processing on the heat output of the device, calorimetric measurements of the cooling water flow were made using thermo sensors AD590 with online data registration by a Data Translation DT9800 series plate. The composition of the products and the combustion efficiency were measured using a Testo 350 gas analyzer. The biomass weight loss rate was estimated from the measurements of the height of the biomass layer in the gasifier by a moving rod with a pointer. Online data registration of the main gasification/combustion characteristics was made once per second.

2. Results and discussion

The microwave pre-processing of straw pellets starts with the removal of the physically bounded water and it is followed by the changes in biomass chemical composition due to the appearance of hot spots, which initiates the breakdown of the glycosidic structure of polysaccharides into smaller fragments, reducing the crystallinity of cellulose and providing carbonization of the cell wall structure [6-10]. The changes in structure at the mw pre-processing of straw pellets are responsible for the enhanced thermo-chemical conversion of the mw-activated wheat straw pellets and their mixtures with wood and with peat pellets, thus increasing the weight loss at their thermo-chemical conversion. The thermo-chemical conversion of the activated straw pellets gives evidence of an increase of the average weight loss rate from 0.1 g/s to 0.12 g/s (by about 20%), with the formation of two sharp peaks in the time-dependent variations of the weight loss rates (Fig. 1-a), which refers to the primary stage of flaming combustion of volatiles ($t \approx 700$-900 s) and to the end stage of char conversion ($t \approx$

1000-1350 s). The DTG analysis of the unprocessed wheat straw pellets showed the formation of a sharp weight loss peak at T ≈ 570 K, which can be related to the thermal decomposition of hemicelluloses and cellulose, and of a less pronounced peak at around 690 K, which can be related to the char formation and conversion [4]. Hence, the results of the DTG analysis of the wheat straw thermal decomposition suggest that the mw pre-processing of straw pellets results in enhanced thermal decomposition of hemicelluloses and cellulose during the primary stage of self-sustaining thermal decomposition of straw pellets and flaming combustion of volatiles with a more pronounced weight loss during the final stage of char conversion. The activation of the thermal decomposition of the mw pre-processed straw pellets make an influence to the combustion process of wood and peat pellets. The average weight loss of the activated straw-wood pellet mixture with the 30% straw mass load increases from 0.11 g/s to 0.127 g/s (≈15.5%), whereas the average weight loss of the activated straw-peat pellet mixture increases from 0.094 g/s up to 0.116 g/s (≈23.4%) (Fig. 1-b,c).





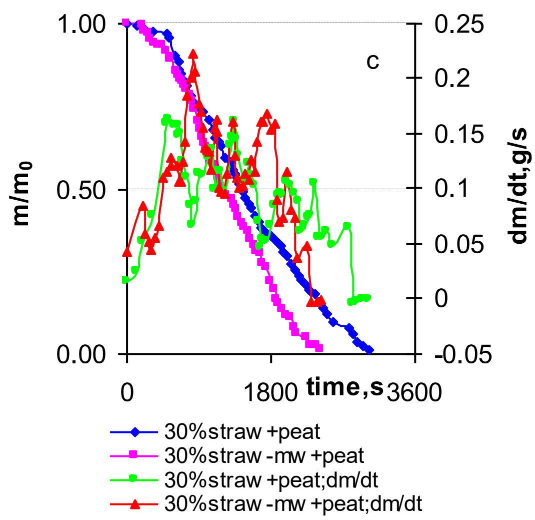


Fig. 1. Effect of mw pre-processing of wheat straw pellets on the weight loss rates at thermo-chemical conversion of straw (a) and of mixtures of straw with wood (b) and with peat (c) pellets

The FTIR measurements of the spectrum of the volatiles produced at the enhanced thermal decomposition of the mixtures showed that the mw pre-processing of straw provides an enhanced release of the combustible volatiles (H_2, CO, C_xH_y) (Fig. 2-a,b). When comparing the kinetics of the formation of volatiles for the activated mixtures of straw with wood or with peat pellets, one can see a difference in time-dependent variations of the formation of combustible volatiles at the thermal decomposition of wood and peat pellets. The mw pre-processing of straw pellets resulted in enhanced release of CO at the primary stage of thermal decomposition (t < 800-1000 s), whereas the peat pellets demonstrated the enhanced release of CO at the final stage of char conversion.

With the unchanging primary and secondary air supply rates into the device, the thermo-chemical conversion of the unprocessed straw mixtures with wood or with peat pellets develops with the average air excess ratio in the flame reaction zone at about α ≈ 1.6-1.7. The enhanced thermal decomposition of the activated straw mixture with wood pellets promotes the enhanced mass flow of combustible volatiles into the combustor that leads to the variation in fuel supply, thus decreasing the average air excess ratio in the flame reaction zone from α ≈ 1.7 to α ≈ 1.4 (Fig. 3-a). When combusting a mixture of activated straw with peat pellets, the average air excess ratio decreases from α ≈ 1.65 to α≈1.35 demonstrating improvement of the combustion conditions, which results in faster and more complete combustion of volatiles leading to the increase of the peak and average values of the heat output from the flame reaction zone and produced heat energy per weight of burned mixture (Fig. 3-b).

At the thermo-chemical conversion of the mixture of activated straw-wood pellets the average heat output from the reaction zone increased by ~25% with the increase of the total heat output from the device by ~12%. The heat output from the reaction zone for the activated straw-peat pellet mixture grew by ~13% with the correlating increase of the total heat output from the device by ~20% and of the produced heat energy per mass of burned mixture by ~6%, which confirms that the mw activation of straw pellets results in more complete thermo-chemical conversion of the mixture.

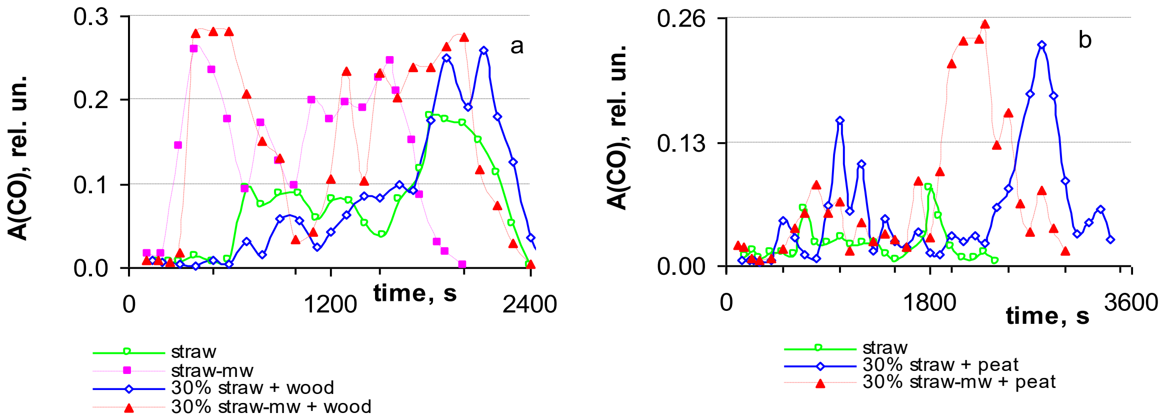


Fig. 2. Effect of mw pre-processing of wheat straw pellets on the release of combustible volatiles (CO) at thermo chemical conversion of activated straw mixtures with wood (a) and with peat (b) pellets

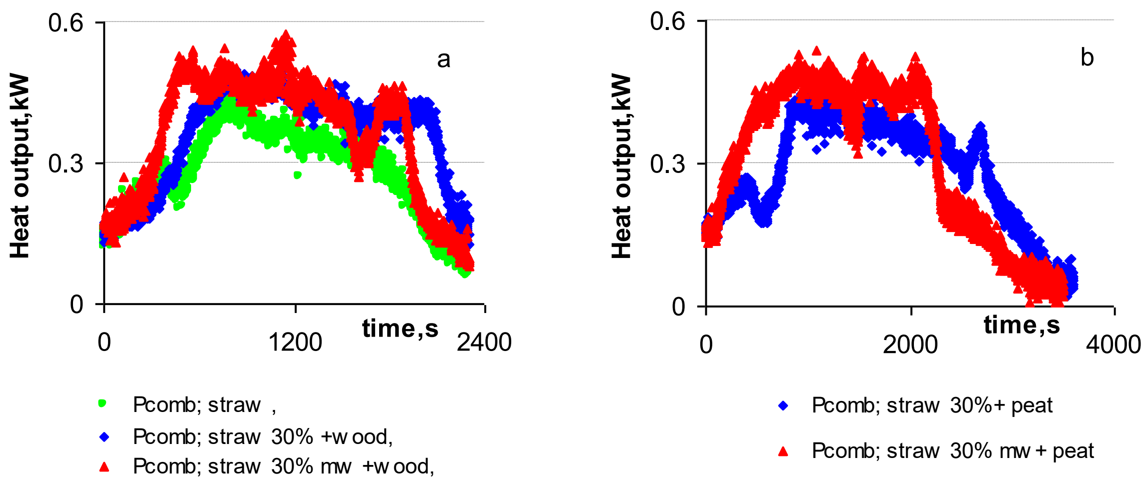


Fig. 3. Effect of wheat straw pellets mw pre-processing on the heat output from the flame reaction zone at thermo chemical conversion of activated straw mixtures with wood (a) and with peat (b) pellets

Finally, it should be noted that the activation of the thermal decomposition of mixtures enhances the composition variations of the emission gas (Fig. 4-a,c). With the activated thermal decomposition of the mixture of straw with wood, the average value of the CO_2 volumes fraction in the products increased by ~2%, whereas for the mixture of straw with peat by ~2.2%. In addition, the co-combustion of straw with wood results in decrease of the average values of the polluting NO_x emissions from 214 ppm to 190 ppm (by ~10%), whereas a slight growth of the NO_x emission in the products (by ~5%) was observed for the mixture of straw with peat, which predominately can be related to the higher nitrogen content in the peat pellets (1.14%) in comparison with straw (1.01%).

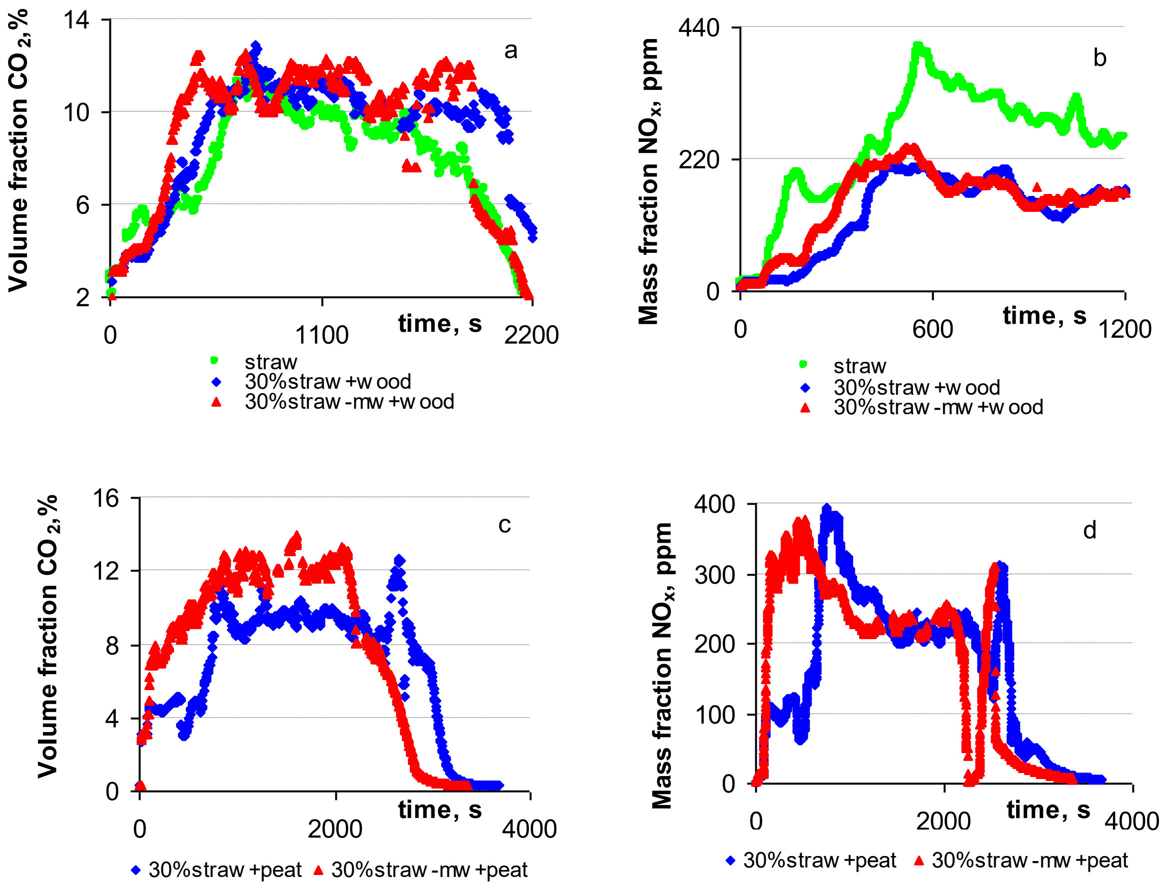


Fig. 4. Effect of wheat straw pellets mw pre-processing on greenhouse carbon (CO_2) (a, c) and polluting NO_x emission (b, d) at thermo-chemical conversion of activated straw mixtures with wood (a, b) and with peat (c, d) pellets

Conclusions

The co-combustion of straw with wood or with peat pellets, with the 30% straw mass load in the mixture, was studied experimentally to provide a wider use of straw as a fuel with a more complete thermo-chemical conversion of pellets, increased heat output from the device and reduced polluting NO_x emission in the products if compared with the thermo-chemical conversion of straw.

Additional improvement of the combustion conditions and composition of emissions is achieved by mw pre-processing of straw pellets. The activation of straw pellets by mw pre-processing provides enhanced thermal decomposition of the activated straw mixtures with wood and with peat pellets promoting enhanced release and more complete thermo-chemical conversion of the combustible volatiles (CO, H_2) and thus increasing the heat output from the device by about 30% at the co-combustion of straw with wood, but with a less pronounced increase of the heat output (by about 8%) at the co-combustion of activated straw with peat.

The enhanced release and more complete thermo-chemical conversion of volatiles result in increase of the average value of the carbon-neutral CO_2 volume fraction in the products by about 2-2.2%. The thermo-chemical conversion of the activated straw mixture with wood pellets leads to reduction of the mass fraction of polluting NO_x emissions in the products by about 10%, with a slight increase (by about 5%) of NO_x emissions at the thermo-chemical conversion of the activated straw mixture with peat, which is the main negative result when co-combusting straw with peat.

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