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Full Length Article

Blended biomass pellets as fuel for small scale combustion appliances: Influence on gaseous and total particulate matter emissions and applicability of fuel indices

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HIGHLIGHTS

- Blending of wheat straw, miscanthus and pine wood was employed to highlight the emission reduction potential of this strategy for small scale combustion appliances.
- Applicability of several fuel indices was confirmed for blended fuels.
- A good correlation was found for the potassium content and the total particulate emission levels.

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ABSTRACT

Non-woody biomass fuels have a great potential to replace fossil fuels and reduce greenhouse gas emissions. At the same time, their application in small scale combustion appliances for heat production is often associated with increased operational problems (e.g. slagging in the bottom ash or fouling) as well as elevated particulate and gaseous emission levels. To mitigate these problems, scope and limitation of blending raw materials owing critical fuel composition with less problematic biomasses have been systematically studied during combustion experiments in a commercially available small scale combustion appliance with a nominal heat capacity of 30 kW. Three pellet batches of pure biomass (i.e. pine wood, miscanthus and wheat straw) as well as seven blended biomass pellet batches have been employed. Slagging, emission of total particulate matter (TPM) and gaseous emissions (i.e. CO, NO_x, SO_2 and HCl) were monitored. The results were evaluated with respect to the emission reduction potential of the blending strategy as well as the applicability of fuel indices which were originally developed for coal and pure biomass fuels. Based on the results, blending of herbaceous raw materials with woody biomass reduces the slagging risk in the bottom ash and leads to reduced emission levels, though significant reduction potential was observed only for blends with at least 50 wt% wood. The blending of miscanthus with wood seemed to be more effective. Most of the fuel indices which were deduced from the chemical composition of the fuel seem to be applicable for a preliminary evaluation of blended biomass fuels and the prediction of critical emission levels.

Abbreviations: bld, below limit of detection; d.b., dry basis; DIN, Deutsche Industrienorm (German industry standard); DT, deformation temperature; EN, European standard; FT, flow temperature; FTIR, fourier transform infrared spectroscopy; GHG, greenhouse gas; HMD, heat metering device; HPLC, high pressure liquid chromatography; HT, hemisphere temperature; ID fan, induced draft fan; M, miscanthus; n.a., not analyzed; OVN, overnight; S, wheat straw; R^2, coefficient of determination; SCR, selective catalytic reduction; SNCR, selective non-catalytic reduction; SST, shrinkage temperature; STP, standard temperature and pressure; TPM, total particulate matter; URV, upper range value; VDI, Verband der Deutschen Industrie (German Industry Association); VOC, volatile organic compounds; vol%, volume percent; W, pine wood; wt%, weight percent.

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1. Introduction

A successful deployment of renewable energy (e.g. solar, wind, water or biomass) not only contributes to the reduction of the fossil fuel consumption, it also has a high potential for climate protection [1]. Non-woody biomass fuels are considered to play an important role to mitigate greenhouse gas emissions in an increasingly complex energy system. The main challenges of non-woody biomass utilization arise from their critical chemical composition, e.g. chlorine, sulfur and mineral content such as potassium being the reason for elevated gaseous HCl and SO_2 as well as particulate emissions and elevated slagging risk in the bottom ash, fouling and corrosion problems [2–9]. In the last couple of years, the combustion and emission behavior of pure, woody and non-woody biomass fuels in small scale appliances have received considerable attention and numerous results have been published on the performance of small scale combustion appliances with a wide range of biomass fuel pellets highlighting specific problems and challenges [10–20]. Usually, mineral additives have been used to mitigate problems resulting from critical fuel characteristics [8,21]. The blending with less problematic biomasses seems to be also effective to improve the fuel properties to achieve stable and efficient boiler operation. First studies on the production of blended biomass fuels were performed [22–25]. In several studies, selected biomass blends and mixed biomass fuels are included in the scope of investigated fuels. However, published data focuses on specific aspects of the combustion process such as kinetic and thermal degradation behavior using TGA experiments [23,25–27], deposition formation of particles [28–31], bottom ash related problems [11,22,27,29–38] and formation of gaseous or particulate emissions [10,11,22,29–35,38–43]. Only few studies with the focus on ash related problems and the formation of NO_x emissions using systematically blended biomass raw materials on lab scale have been performed [26,36,40,41,44]. Fuel indices have been suggested for a preliminary qualitative evaluation of several combustion related aspects such as gaseous and particulate emissions, slagging and corrosion tendencies of pure non-woody and woody biomass as well as fossil solid fuels. Based on numerous studies performed with selected biomass fuels in dedicate bench and lab scale facilities, several indices with good prediction potential for NO_x emissions [15,19,31,38,41,43,45,46], aerosol or total dust emissions respectively [10,11], gaseous HCl and SO_2 emissions [10,11,15,19,31,38,47–50] and slagging tendencies in the bottom ash [9,14,51–55] could be identified. In the work of Sommersacher et al. [56] these fuel indices were checked and evaluated regarding their applicability by measurements performed in lab- and real-scale combustion systems for a variety of pure biomass fuels such as spruce, bark of softwood, waste wood, poplar, miscanthus, wheat straw, olive kernels, maize spindle, grass pellets, sewage sludge or decanter and rapeseed press cake. It was shown that the fuel indices can provide a first pre-evaluation for emission levels and slagging tendencies. The applicability of these fuel indices was further verified for the combustion of wood/kaolin and straw/kaolin as well as miscanthus/peat blends [57,58]. No systematic investigations were published for blended biomass fuels. In this work we aim to highlight the potential and limitation of biomass blending for reduction and the applicability of fuel indices for such blended fuels. The used pellets were made from woody and herbaceous raw materials in specific ratios. The combustion experiments have been performed in a dedicated commercially available small scale combustion appliance.

2. Material and methods

2.1. Fuels

The raw materials used in the present study were pine wood shavings (W), wheat straw (S) and miscanthus (M). The pine wood shavings were delivered from a commercial pellet company located in Germany. The energy crop miscanthus (*Miscanthus x Giganteus*) was grown on a post-mining area, collected with a forage harvester and purchased as chopped material (length approx. 30 mm) from Agrarproduktion Elsteraue GmbH & Co. KG, Zwenkau in Saxony/Germany. After harvesting, miscanthus chops had a moisture content of approximately 10 wt%. Thus, technical drying was not required. Wheat straw bales were purchased from Agrarhandel & Transport GmbH, Schafstädt in Saxony-Anhalt/Germany. For the herbaceous raw materials we expected rather inhomogeneous fuel characteristics. Thus, five individual samples were analyzed both from the miscanthus and the wheat straw raw material batches. Three pure and seven binary blended biomass pellet batches were produced by PTG Pelletier- und Transportgesellschaft GmbH, Apolda in Thuringia/Germany in an industrial ring die pellet press with a nominal capacity of 1 t/h, Table 1. For the production of bended biomass pellets, the comminuted biomasses were thoroughly mixed and then pelletized.

Each batch had a weight of approx. 500 kg. For analyses, samples were taken using a sampling pipe according to DIN EN 14778 which was introduced in the middle of a big bag of each fuel batch [59]. The merged fuel samples obtained from the sampling pipe were analyzed according to the European standards for solid biofuels: bulk density, mechanical durability, proximate analysis, water content, ash content, ash melting behavior, total content of sulfur and chlorine, lower heating value, major elements (i.e. Al, Ca, Mg, P, K, Si and Na, hydrofluoric digestion) and minor elements (i.e. Pb and Zn, hydrofluoric digestion) [60]. The analysis data was compared with the values calculated by the application of the mixture rule.

2.2. Combustion experiments

2.2.1. Test bench

The combustion experiments were performed in a commercially available boiler dedicated for the combustion of wood pellets and energy grains which has a nominal heat capacity of 30 kW. The biomass fuel is conveyed by the feed auger into the combustion chamber with a moving step grate ensuring the transport of the bottom ash into the ash pan. A lambda control supports optimal fuel feed rates. An ID fan supplies the combustion air to the boiler. The combustion air ratio can be manually adjusted by a baffle to direct the primary combustion air to the moving grate and the secondary combustion air to the post combustion chamber. Heat exchange was realized using a jacket-and-tube heat exchanger which was cleaned automatically by moving turbulators. The boiler was equipped with temperature measurement devices (type K, diameter 3 mm) in the fuel bed and in the secondary combustion chamber to monitor the combustion process. The boiler was integrated into a local heating circuit which was actively cooled by a re-cooling unit to ensure a constant minimal cold water return temperature of 60 °C. The flue gas duct complied with the requirements of DIN EN 13284-1 [61], Fig. 1.

The gaseous flue gas components CO, NO_x, SO_2 and HCl were monitored online using a FTIR, type CX-4000 (ANSYCO GmbH) and an O_2 analyzer, type PMA 100-L (M&C TechGroup Germany GmbH), Table 2. The sampling line and probe were heated to 180 °C. TPM emissions were measured by using the gravimetric method according to VDI 2066 [62]. For the sampling, the out stack method and the automatic isokinetic control unit ITES (Paul Gothe

Table 1
Applied pure and blended fuels (ratios of raw materials are given in wt%).

Pellet	Wood (W)	Miscanthus (M)	Wheat straw (S)
100W	100	–	–
100M	–	100	–
100S	–	–	100
70W30M	70	30	–
50W50M	50	50	–
30W70M	30	70	–
70M30S	–	70	30
50M50S	–	50	50
50W50S	50	–	50
70W30S	70	–	30