Full Length Article

Blended biomass pellets as fuel for small scale combustion appliances: Effect of blending on slag formation in the bottom ash and pre-evaluation options

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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 deposit formation) as well as elevated gaseous and particulate matter 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) and seven blended biomass pellet batches have been employed. Slag formation in the bottom ash as well as amount of agglomerated bottom ash particles were monitored and evaluated with respect to the determined ash melting temperatures and the measured fuel bed temperatures. Significant reduction of the slagging risk in the bottom ash during combustion of herbaceous fuels can only be achieved for high blending ratios with more than 70 wt% wood. It was furthermore studied to which extent fuel indices are applicable for the prediction of the bottom ash behavior of blended biomass fuels. Furthermore, ternary diagrams were used to rationalize the observed slagging characteristics. It was found that ternary diagrams are superior for a pre-evaluation of the slagging risk in the bottom ash to fuel indices alone. With the knowledge of the fuel ash composition and the ash melting temperatures, a well based pre-evaluation of utilization options can be performed.

1. Introduction

Application of biomass fuels for heat and power generation can contribute to the reduction of greenhouse gas (GHG) emissions which is crucial to reach the ambitious targets set by the United Nations Climate Change Conference (Paris agreement) [1]. For heat and power production on MW scale, wood and to some extent straw and other biomasses are used [2,3]. In Germany, wood fuels (i.e. log wood, wood chips and wood pellets) are the predominant biomass fuels for small scale heating – up to 100 kW. However, in several regions the rapid increase in wood pellet production resulted in raw material shortage [4,5]. Since wood assortments are also considered as promising raw materials for the evolving biorefinery sector [6], this competition is expected to substantially increase in the future. Thus, to fulfill the

anticipated growth of biomass utilization in the European heating and cooling sector from 2225 PJ to 3785 PJ between 2005 and 2020 (3046 PJ were achieved in 2012) [7], a wider assortment of raw materials will be required including low quality wood fuels (e.g. logging residues, short rotation coppice) and non-woody biomasses. Based on their high potential and prevalent availability, agricultural side products like straw as well as other herbaceous residues like hay are regarded as the most important non-woody biomass fuels. Many other regional available raw materials and biogenic residues might also be considered and a wide variety including pruning, pits, shells, grasses, grains and seeds as well as various processing residues have been tested as potential fuels [8–26]. Compared to stem wood, all these materials are usually characterized by a higher ash content and a large variation in the composition of ash forming elements [27–29]. Herbaceous fuels are usually

rich in silica and the silicon content of the biomass ash may sum up to more than 90 wt%, e.g. in cereal husks [27,30–32]. Woody biomass assortments uncontaminated by soil impurities are composed predominantly of alkaline earth metals with silicon and potassium coming next [30,33–36]. In contrast, some energy crops as well as grains and seeds often contain significantly higher amounts of phosphorus resulting in low Si/P ratios compared to woody and herbaceous biomass [27,37,38]. Based on the higher ash content and the distinctive fuel composition, the application of the different biomass fuels for bioenergy production is often associated with elevated gaseous and particulate emission levels contributing to deposit formation or high temperature corrosion as well as operational problems resulting from low ash melting temperatures, i.e. impeded ash removal during fixed bed combustion or bed agglomeration in fluidized-bed combustion systems. The critical combustion behavior of biomass fuels originates mainly from the interaction of the elements K, Si, Na, S, Cl, Ca, Mg, P, and Al resulting in biomass ashes which are mainly comprised of inorganic amorphous, crystalline and semi-crystalline constituents [31,39].

In the last decade, extensive research has been performed to gain a better understanding of the complex mechanism of ash transformation processes during slag formation in the bottom ash [31,39–42] that also influences the release of particulate matter during complete combustion [8–10,31,37,40,43,44]. Ash melting behavior mainly relies on the relative concentrations of the ash-forming elements, the total amount of critical compounds and their kinetic properties [31]. However, also the association of the ash-forming elements as well as their distribution in the biomass fuels strongly affects the final ash melting behavior [43]. Based on thermodynamic considerations, a scheme for ash transformations was suggested by Boström et al. that is helpful to rationalize the compositional effects on slag formation and release behavior [31].

As a consequence of its highly volatile nature, a substantial share of the fuel potassium is released to the gas phase during combustion. Thus, especially the retained share will participate in the slag formation in the bottom ash which is influenced by various parameters. At lower temperatures more potassium is retained in the bottom ash [45,46]. Furthermore, some elements either inherent or used as additives may amplify potassium retention, e.g. silicon or sulfur [38,40,43,47,48]. In particular, alumo-silicates have been proven to bind considerable amounts of potassium [12,49–52]. During systematic studies of rice straw/wood blends, it has been shown that the addition of > 30 wt% rice straw resulted in highly polymerized silicates evoking an amplified retention of potassium in the bottom ash [40]. Other elements impede with potassium retention like chlorine that leads to an increased potassium release in the form of KCl. Alkaline earth metals such as magnesium and calcium compete with potassium for network positions in the silicate network and consequently can also cause lower potassium retention in the bottom ash [40,43].

Empirical correlations have been identified that resulted in fuel indices for the prediction of elevated slagging tendencies in the bottom ash providing a useful simplification of the complex ash transformation processes [29,31,42,43,53]. The correlation of the slagging tendency in the bottom ash with the relative amount of silicon and alkaline earth metals has been demonstrated by various authors [43,53]. For phosphorus rich fuels an extended slagging index $(Si + P + K)/(Ca + Mg)$ has been proposed by Sommersacher et al. [53,54]. For biomass fuels with additives, adapted indices were suggested [50]. Knudsen et al. studied in detail the interaction of silicon, potassium and alkaline earth metals for various fuel assortments [43]. According to their studies, the molar ratios of Si/K and $(Ca + Mg)/Si$ provide a good indication about slagging in the bottom ash during combustion processes [43]. High molar Si/K ratios (i.e. > 2.5) indicate an increased retention of potassium in the bottom ash [43]. However, retention of potassium in silicon rich fuels will be impeded by high chlorine contents reflected by molar K/Cl ratios < 10 [43]. For silicon rich fuels with low chlorine content, a low molar $(Ca + Mg)/Si$ ratio indicates higher potassium retention rates in the bottom ash [43]. Consequently, though useful for

providing a first indication fuel indices still have to be handled with care since the simplification also restricts the general use and usually several indices have to be considered simultaneously.

To some extent, the latter aspect has been addressed by ternary phase diagrams allowing for the incorporation of information on phase transition and melting temperatures originating either from empirical findings or from thermodynamic equilibrium calculations. Their usefulness for the prediction and interpretation of ash related problems has been demonstrated for pure woody and non-woody fuels in several studies [31,38,55–59]. However, thermodynamic data is still lacking for critical biomass ash systems and still needs experimental investigations [56,57].

To enable and facilitate the utilization of a wide range of biomass fuels in combustion systems, several strategies to mitigate the ash related problems have been employed. Most commonly, additives are used addressing low ash melting temperatures and the release of critical elements in the flue gas [60]. Using this strategy, slagging in the bottom ash is reduced by the introduction of compounds that capture problematic ash components forming higher melting compounds or by diluting the ash with inert, high melting materials. However, for biomass fuels with elevated ash content the utilization of additives further increase ash removal problems during boiler operation [61]. Alternatively, strategies can be employed to reduce the content of critical elements in the biomass fuel ash. For dry herbaceous raw materials leaching has been successfully applied [27,62–67]. The content of critical elements in fresh grass and foliage samples was substantially reduced by mechanic dewatering [68–70]. Reduction of ash content and relative amount of critical elements can also be achieved by blending with less problematic biomass fuels (e.g. wood, miscanthus or peat) [14,37,41,58,71–75]. The blending furnishes a different ash composition resulting in deviating ash melting and release behavior. For example, Sommersacher et al. demonstrated with miscanthus/peat blends that the potassium release is decreasing with peat shares until 50 wt% and that for lower peat shares of 0–25 wt% potassium release is rather constant [58]. Thy et al. experimentally studied the melting of wood/rice straw ash blends with up to 50 wt% rice straw ash. It was demonstrated that the addition of rice straw (i.e. in particular for blends with > 30 wt% rice straw) reduces the relative loss of potassium, lowers the melting point, and increases the total volume of bottom ash and slag [40]. This trend was also confirmed by Schmitt et al. [41]. Nonetheless, application of biomass blending to reduce slag formation in the bottom ash is still limited and systematic investigations are scarce. For these reasons, the objective of this work was to study the effectiveness of blending wheat straw, miscanthus and pine wood to reduce slagging tendencies in the bottom ash and the possibilities to predict the ash melting behavior based on ternary phase diagrams.

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. Three pure and seven binary blended biomass pellet batches were produced by PTG Pelletier- & Transportgesellschaft GmbH, Apolda in Thuringia/Germany in an industrial ring die pellet press with a nominal capacity of 1 t/h, Table 1. The blending ratios were selected to map out the usefulness of the approach and to cover the complete range of possible fuel