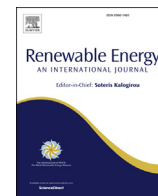




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## Ash melting behaviour of wheat straw blends with wood and reed

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## ABSTRACT

Combustion of fuel blends is becoming more important. During combustion, interactions between ash-forming elements and compounds of different fuel blends can occur. Blending without sufficient knowledge and analysis can easily lead to operational problems, such as slagging, fouling and corrosion. Focus in our study is on the ash behaviour of wheat straw pellets blended with reed (*Phragmites australis*), wood pellets, and Douglas fir wood chips. The standard method (procedure) of CEN/TS 15370 and STA or simultaneous thermal analysis (thermogravimetric analysis (TGA) coupled with differential thermal analysis (DTA)) were applied to characterize the ash behaviour of the fuel blends studied. The ash melting behaviour of the blend of fuels depends not only on the composition, but also on the content of mineral matter of a single fuel. Low melting eutectics are possible when the K and/or Si-containing fuels are blended.

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## 1. Introduction

To predict ash-related problems, detailed knowledge of the fuel being fired is required. The amounts of ash-forming elements vary between different types of biomasses. The main ash-forming elements in solid biofuels are silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), magnesium (Mg), manganese (Mn), sodium (Na), potassium (K), phosphorus (P), sulphur (S), and chlorine (Cl). Ash-forming matter is usually divided into four categories: water-soluble salts; organically associated ash-forming elements in the form of ion-exchangeable metal ions of covalently bonded non-metals; included minerals; and excluded minerals, which originate from fuel impurities [1].

Successful operation of co-firing units depends on the content and composition of the fuels. During combustion, interactions between the ash-forming elements and compounds of different fuels in the blend will occur. When the fuels are blended, the properties of the ash formed cannot be predicted directly according to the ash behaviour of a single fuel, since the behaviour of the inorganic and some organic constituents is not necessarily in a linear relationship with the amount of each fuel in a blend. The ash transformation during the combustion of biomass is a very complex phenomenon, which can exhibit many essentially different scenarios. Therefore,

blending without sufficient investigation and analysis can easily cause operational problems, such as slagging, fouling and corrosion, leading to reduced efficiency, capacity and availability of facilities, thereby increasing the power cost. Surprises or unexpected behaviour – some favourable and many unfavourable – may occur with blending when the behaviour of the fuel blend under combustion conditions is insufficiently explored. Hence, knowing the impact of a certain blend on the properties of the final ash is essential when choosing suitable combinations with desired ash melting properties and behaviour [2–5].

A number of methods and techniques have been applied to determine the melting behaviour of ash, such as standard methods (e.g., CEN/TS 15370) using hot stage microscope (HSM) [6], simultaneous thermal analysis (STA) [7,8], thermo-mechanical analyser [9,10], ash viscosity measurement [11,12], electrical resistivity or conductance measurement of ash [13], and the compression strength method [14]. The main disadvantages of standard methods reported are poor repeatability and reproducibility [10] as well as the delay in the temperature (e.g., 40–110 °C) in the determination of melting onset [13].

The by-products and wastes of agricultural and wood industries are a major source of the biomass used in the production of biofuels and biomaterials [15]. Different types of biomasses have been investigated for energetic purposes: wood chips, and co-combustion of reed canary grass and barley straw with wood chips [16]; different agricultural fuels [17], apple pomace, pectin waste from citrus shells, sunflower husk [18]; different blends of

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waste wood, demolition wood and coffee waste [19], corn stover and wood chips blends [20], and reed [21–24]. Clearly, the demand for biomass fuels leads to the co-combustion of wood, wood and herbaceous/agricultural biomasses, and the introduction of new biomass fuels into the market. The combustion behaviour [25], incl. ash melting behaviour of all new biomass fuels, especially the usage of their blends, is not well defined. There is a lack of data about the ash melting behaviour of biomass blends in different proportions.

In general, wood is commonly used as a feedstock for heat and power production and it is relatively easy to burn. However, there are several types of agricultural and herbaceous biomass residues that are difficult to burn; thus, they are still unused or not used in large scale applications. The aim of our investigation of the ash behaviour of different fuel blends is to introduce low-grade residue fuels into the market.

This paper presents the results of our study on the ash behaviour of a variety of fuel blends using different ratios of fuels: 1) wheat straw pellets and wood pellets; 2) wheat straw pellets and Douglas fir wood chips; 3) wheat straw pellets and reed. Besides the potential use as a feedstock, these fuels differ by their nature, properties and chemical composition of mineral matter, and it serves a goal to avoid any possible interferences that could shadow the results compared with the tests carried out when blending the same type of biomass. The results obtained by using the standard ash melting characterization method of CEN/TS 15370 are presented. Additionally, the height loss curve of the test piece (cylinder) determined by the standard ash melting characterization method of CEN/TS 15370 was combined with the results obtained by applying simultaneous thermal analysis (STA).

## 2. Materials and methods

### 2.1. Materials

Four parent biomass fuels were selected to study the ash behaviour of different fuel blends: wheat straw pellets (WSP), wood pellets (WP), Douglas fir wood chips (DF), and reed (R). WSP originates from northern part of Lithuania, WP from the Ebavere pellet factory in Estonia, and DF, which contains bark that originates from the Bavaria area in Germany. Reed (R) originates from the west-coast areas of Estonia.

### 2.2. Characterization of parent fuels and ashes

The used parent biofuels were prepared and characterized by proximate analysis (according to the standard methods of CEN/TS 14774-1:2004, CEN/TS 14775:2004, CEN/TS 15148:2005), ultimate analysis (according to the standard methods of EN 15104:2011, EN 15289:2011) using a Vario EL CHNOS Elemental analyser, and gross calorific value (according to the standard method of EN 14918) using an IKA C 5000 calorimetric bomb.

The X-ray fluorescence (XRF) technique was applied to determine the elemental composition of the ashes of parent fuels using a Rigaku ZSX Primus II WDXRF device with a Rhodium anode 4 kW and a 30  $\mu\text{m}$  tube. The loss of ignition (LOI) determined according to the standard method of ISO 1171 has been considered as well.

### 2.3. Ashing procedure

The standard method of CEN/TS 14775:2004 was applied as the ashing procedure. The thermal cycle is as follows: 1) from room temperature to temperature of 250 °C with a heating rate of 4.5 °C/min; 2) hold of 60 min at 250 °C; 3) heating to 550 °C with a heating rate of 10 °C/min; 4) hold of 120 min at 550 °C; 5) cooling down to room temperature.

### 2.4. Ash fusion

#### 2.4.1. Standard method

The ash melting characteristics were determined in an air environment according to the standard method of CEN/TS 15370-1:2006 using a Misura 3 HSM ODHT 1600–5008 device. In this method, the melting behaviour of the ash is described as temperatures at which the sample has typical shapes: shrinkage starting temperature (ST) corresponds to the temperature at which the area of the test piece falls below 95% of the original test piece area; deformation temperature (DT) corresponds to the temperature at which the first sign of rounding edges of the test piece occurs due to melting; hemispherical temperature (HT) corresponds to the temperature at which the test piece forms approximately a hemisphere, i.e. the height becomes equal to half the base diameter; and the flow temperature (FT) corresponds to the temperature at which the ash is spread over the supporting tile in a layer, the height of which is half of the height of the test piece at the hemisphere temperature. During the tests, also the height of the test piece over the temperature was recorded. For each ash sample, two tests were made and the repeatability expressed as the absolute difference was as follows: 26 °C for ST; 72 °C for DT, 17 °C for HT, and 11 °C for FT. The repeatability is at an acceptable level (see also [Introduction Section](#)) in this method and the general trend of the melting behaviour of studied samples remains unaffected.

#### 2.4.2. Simultaneous thermal analysis

TA Instruments SDT Q600 device was used for simultaneous thermal analysis (STA) of ashes, i.e. thermogravimetric analysis (TGA) coupled with differential thermal analysis (DTA). The sample was heated from room temperature up to the final temperature with a heating rate of 10 °C/min. The mixture of 13 ml/min O<sub>2</sub> and 87 ml/min N<sub>2</sub> was used as carrier gas. The maximum temperature achievable with the device is 1300 °C. If the standard ash melting test gave a flow temperature below 1300 °C, a lower temperature of around 30° higher than the flow temperature was applied as the final temperature.

### 2.5. Preparation of fuel blends

The parent fuels were blended in different proportions using a step of 20 weight-% “as received” basis. Thus, four blends were prepared for each pair of parent fuels. The fuels in blends were mixed and targeted to ashing according to the above described standard ashing procedure of CEN/TS 14775:2004.

## 3. Results and discussion

### 3.1. Fuel characterization and composition

[Table 1](#) shows that WSP has the highest ash content (4.5% dry basis) and WP the lowest ash content (0.5% dry basis) of the parent fuels. Due to the low ash content of WP, the organic part is proportionally higher, resulting in higher gross calorific value as well.

Based on the XRF analyses, the composition of the parent fuel ashes is given in [Table 2](#). Though Na<sub>2</sub>O content is higher for DF and R ashes compared to WSP and WP, the sodium content is relatively low for all studied ashes. The content of MgO, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> is the highest for the DF sample. SiO<sub>2</sub> content is very high in R ash, e.g. 1.8 and 5.3 times higher than in DF and WSP ashes, respectively. WSP ash has the highest P<sub>2</sub>O<sub>5</sub>, SO<sub>3</sub>, Cl, and K<sub>2</sub>O contents. WP ash exhibits the highest content of CaO. WSP and WP have the highest contents of alkali and alkaline earth oxides. In all ashes, the content of K<sub>2</sub>O is high and in WSP both K<sub>2</sub>O and Cl contents are very high, 24.1 and 5.7 wt%, respectively. The SiO<sub>2</sub> content varies within wide ranges;

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