



## Composition and sintering characteristics of ashes from co-firing of coal and biomass in a laboratory-scale drop tube furnace

Chao Luan<sup>a,b</sup>, Changfu You<sup>a,\*</sup>, Dongke Zhang<sup>b</sup>

<sup>a</sup> Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

<sup>b</sup> Centre for Energy (M473), The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

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### ABSTRACT

In this study ash  $T_s$  (sintering temperature) is proposed as an index to evaluate deposition propensity during coal and biomass co-firing. The experiments were carried out in a drop-tube furnace and the resulting ash samples were collected.  $T_s$  of the ash samples was measured with a pressure-drop sintering device. The chemical compositions and mineral phase characteristics of the ashes were also analyzed using ICP (inductively coupled plasma), SEM (scanning electron microscope) and XRD (X-ray diffraction), respectively.  $T_s$  decreased with increasing the mass ratio of biomass to coal with a non-linear relationship. The straw showed a more significant effect on the ash sintering temperature than the sawdust. The limitation of contents in the fuel blends should be 15% and 50% for straw and sawdust, respectively. SEM analysis indicated that biomass promoted ash deposition by accelerating the formation of neck between ash particles. Transformations of the mineral matter to lower sintering temperatures during co-firing had occurred.

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### 1. Introduction

Biomass is an environmentally friendly primary energy source. It is widely considered to be  $\text{CO}_2$  neutral because it consumes the same amount of  $\text{CO}_2$  from the atmosphere during growth as is released during combustion [1–8]. The contents of N and S in most biomass are relatively low compared with coal, and therefore the emissions of  $\text{SO}_x$  and  $\text{NO}_x$  are reduced with the use of biomass [9–14]. Due to the advantages it possesses, biomass is becoming a more and more crucial alternative energy source nowadays. Agricultural and forest residues and purpose-grown energy crops are now major EU (European Union) energy resources [15,16]. Among all the biomass utilization methods, co-firing of biomass with coal is the most promising one. Besides the environmental benefits it brings, co-firing is also the most cost-effective approach to biomass utilization in the power generation industry [17,18]. Some researchers indicated that co-firing can also improve boiler efficiency and combustion performance [3].

Nevertheless, potential risks and constrains exist for the biomass co-firing in utility boilers, for example, ash deposition (slagging and fouling), corrosion, ash utilization, fine particle

emission and etc. [19]. This research is mainly concerned with the ash deposition during co-firing of coal and biomass. Ash deposition is the most common problem encountered in industrial and utility boilers co-firing coal and biomass [20,21]. As is known, biomass ash has relatively low fusion temperature due to high contents of alkali metal species, particularly potassium and, to a lesser degree, sodium, contained in the inorganic matter in biomass [12]. Potassium and sodium can significantly lower the fusion temperature of ash, and hence promote ash deposition in the boiler plants [10,22–26]. Biomass is rich in chlorine compared with coal, which also plays an important role in ash deposition.

The ash deposition during co-firing of coal and biomass has been studied by many scholars and plenty of demonstration and commercial biomass co-firing power plants have been reported [27–30]. Hansen et al. [31] developed a semi-empirical model based on thermodynamic equilibrium calculations to predict the stable forms of sodium and potassium. Pronobis [32] adopts the empirical indices used in dedicated coal combustion to evaluate the deposition tendency of biomass co-firing. However, there has been no method accurate or reliable enough for the evaluation of ash behavior during biomass co-firing up to now, and deposition is still far from being solved [1,17]. Moreover, the study on the effect of biomass types and ratios in the fuel blends on ash deposition behavior is still scarce.

\* Corresponding author. Tel./fax: +86 10 62785669.

E-mail address: [youcf@tsinghua.edu.cn](mailto:youcf@tsinghua.edu.cn) (C. You).

In this research, a deposition index, the ash Ts (sintering temperature), was proposed to evaluate the deposition propensity during biomass co-firing. Co-firing was carried out in a drop tube furnace and the ashes were obtained. Ts of the residual ashes was measured with a pressure-drop sintering device. The pressure drop technique has been employed to study the sintering behavior of coal ash [33], but few researchers have used it in the field of biomass co-firing. The chemical compositions, morphology and mineral phase characteristics of the ashes were also analyzed using ICP (inductively coupled plasma), SEM-EDS (scanning electron microscope + energy dispersive spectrometer) and XRD (X-ray diffraction), respectively. The transformation of chemical compositions of the ashes during co-firing coal and biomass was also discussed.

## 2. Relevance of sintering to ash deposition behavior

Sintering is referred to as the bonding or welding of adjacent particles under the influence of the excess surface tension [34]. An important stage of ash deposition on gas circuits and heat exchanger surfaces was reported to be sintering of the alkali condensate on the surface [35,36]. Gibb [37], Tonmukayakul [38] and Moilanen [39] indicated that ash deposition is predominantly determined by the neck growth between ash particles which is caused by sintering, as shown in Fig. 1. According to Raask [40], the deposits cannot be removed by soot-blowing, when the ratio of the neck radius to the particle radius which is  $x/R$  in Fig. 1 is greater than 0.3.

Obviously, ash with high sintering tendency (low sintering temperature) is expected to have high deposition tendency, and vice versa. As a result, sintering temperature can be regarded as a significant criterion for ash deposition behavior during co-firing of coal and biomass.

## 3. Experimental

### 3.1. Sample preparation

One Chinese bituminous coal from Yanzhou Coal Mine and two typical kinds of biomass, a wheat straw and a pine sawdust, were employed in the experiments. Proximate analysis, ultimate analysis, high heating value as well as ash chemical composition tests were carried out. The results are listed in Table 1.

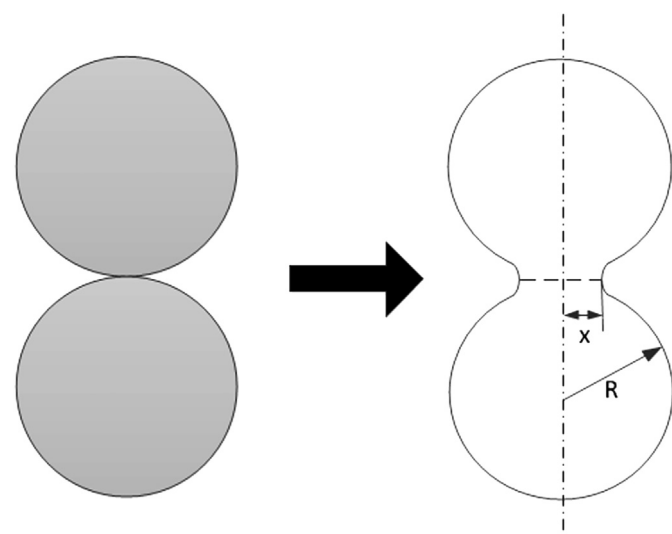


Fig. 1. Schematic of sintering phenomenon ( $x$ : radius of neck,  $R$ : radius of particles).

**Table 1**  
Fuel analysis.

	Wheat straw	Pine sawdust	Bituminous
<b>Proximate analysis (air dried basis, wt%)</b>			
Moisture	9.89	10.09	2.29
Ash	5.22	0.71	8.62
Volatile matter	68.39	76.83	34.69
Fixed carbon	16.50	12.37	54.39
HHV (MJ kg <sup>-1</sup> )	16.02	17.90	28.99
<b>Ultimate analysis (dry ash free basis, wt%)</b>			
C	45.55	49.61	82.46
H	5.70	5.70	5.06
O <sup>a</sup>	46.53	44.47	10.31
N	1.32	0.19	1.49
S	0.15	0.01	0.67
Cl	0.75	0.02	0.01
<b>Ash composition (wt%)<sup>b</sup></b>			
Al <sub>2</sub> O <sub>3</sub>	1.67	2.74	36.41
CaO	4.80	35.91	4.01
Fe <sub>2</sub> O <sub>3</sub>	1.01	2.46	6.57
K <sub>2</sub> O	32.60	21.39	0.45
MgO	5.09	12.66	1.22
MnO <sub>2</sub>	0.17	0.67	0.08
Na <sub>2</sub> O	13.24	2.93	0.65
P <sub>2</sub> O <sub>5</sub>	7.72	5.09	0.11
SiO <sub>2</sub>	30.09	12.68	48.08
TiO <sub>2</sub>	0.15	0.24	1.97
SO <sub>3</sub>	3.45	3.24	0.45
Cl	1.97	0.24	0.08

<sup>a</sup> By difference.

<sup>b</sup> The ashing method of coal was in accordance with the Chinese Standard GB/T 212-2001; the ashing method of biomass was in accordance with the Chinese Standard NY/T 1881.5-2010.

The coal was ground to a size fraction of <100 μm. The straw and sawdust were ground using a blender and sieved size fraction of <1 mm and <0.8 mm, respectively. Altogether, 3 single fuels and 8 blended fuels among them, were used in the experiments. The contents of coal and biomass in the fuel blends used in the experiments are shown in Table 2.

### 3.2. DTF (Drop tube furnace)

The fuel blends of coal and biomass were burned in a DTF. The inner diameter of the ceramic furnace tube was 50 mm, and the length was 1000 mm. A sampling tube was inserted into the furnace at the bottom to capture the residual ash. First, the furnace was heated to 1500 °C which is of typical flame temperature in boilers to simulate the real combustion conditions. When the furnace temperature was stabilized, the blends of coal and biomass were dropped from the top of the furnace with a feeder, aided with an air flow at 15 L/min. The residence time of the fuel particles in the combustion zone was estimated to be about 1 s. In each case, the excess air ratio was 1.3 by controlling the feeding rate of the fuel. The residual ash was captured by the sampling probe and separated in an ash separator. About 2 g ash was obtained for each type of fuel blends.

### 3.3. PDS (Pressure-drop sintering device)

The sintering temperature of ash can be determined by several techniques, for example, the compression strength method, electrical conductance technique, pressure drop technique [41]. Of all these measuring methods, the pressure drop technique, which has been depicted by Wee et al. [33], is the most reliable one to provide an accurate indication of the sintering temperature due to its sensitivity to structural changes of ash pellets [41].

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