



Full Length Article

Effect of particle size on particulate matter emissions during biosolid char combustion under air and oxyfuel conditions

Sui Boon Liaw^a, Xujun Chen^a, Yun Yu^a, Mário Costa^b, Hongwei Wu^{a,*}^a Discipline of Chemical Engineering, Western Australian School of Mines: Minerals, Energy and Chemical Engineering, Curtin University, GPO Box U1987, Perth, WA 6845, Australia^b IDMEC, Mechanical Engineering Department, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

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ABSTRACT

In an industrial scale furnace, solid fuels can be fired in a wide range of particle sizes. This study aims to investigate the effect of the particle size on particulate matter (PM) emissions during combustion under air and oxyfuel (30% O₂/70% CO₂) conditions. Biosolid chars prepared from the pyrolysis of three different biosolid particle sizes at 1300 °C were burned in a drop tube furnace. The experimental results indicate that a shift from small to large char particles leads to > 55% reduction in PM_{1–10} emission when combustion occurs in air, likely due to less intense char fragmentation experienced by the large char particles. Such a reduction originates from a decrease in Mg, Ca, P, Si, Al and some trace elements (V, Co, Cu, Zn and Mn) release as PM_{1–10}. In contrast, PM₁ emission is not affected by the char particle size. However, under oxyfuel conditions, the PM_{1–10} emission from the small char particles is ~65% of that released during combustion in air. In addition, the PM_{1–10} emission from large char particles only reduced by ~27% when compared to that from small char particles. This observation is likely to result from the coalescence of ash particles to form PM with particle sizes > 10 μm due to the increase surface mobility caused by repeated formation and decomposition of CaCO₃ in the ash.

1. Introduction

Biosolid is a byproduct from wastewater treatment processes and has generated significant environmental issues for disposal, mainly due to its high contents of toxic organic compounds and heavy metals [1]. Among the available technologies for biosolids utilisation, combustion is one of the most effective strategies not only to achieve a large volume reduction but also to recover the energy in the biosolid [2]. However, combustion of various fuels are known to release particulate matters (PMs) that have potential hazard to the human health and to the environment (soil, air, and water) [3–9]. This is of particular concerns because biosolid contains high content of ash, resulting in PM significant emissions of during combustion [8,9]. A large portion of trace metals (i.e., Cu, Cr, Ni, Pb, V, Co, Cd and As) present in biosolid are also released in the PM during combustion [10]. Therefore, it is of critical importance to understand the emissions of PM and trace elements during the combustion of biosolid.

Usually, biosolid is fired under air conditions in boilers to generate electricity [2]. Recently, there has been an increasing need to develop oxyfuel combustion technology in order to facilitate carbon capture and storage and, thereby, to achieve negative carbon emissions from

biosolid-fired power plants [11]. Although PM emissions from biosolid combustion under air conditions are relatively well documented in the literature [2,8,12,13], studies on oxyfuel combustion of biosolid are scarce. Surprisingly, the release of trace elements in the PM during the combustion of biosolid under oxyfuel conditions is also seldom reported. In order to address this problem, this work presents a systematic study on the emissions of PM (including major and trace elements) during the combustion of biosolid in both air and oxyfuel environments. A distinct feature of this work is the emphasis placed on the effect of the particle size on PM emissions that, to the best of our knowledge, has not been considered before. Furthermore, to eliminate the possible effect on the PM emissions of the combustion of the volatiles [14], biosolid chars were first produced from pyrolysis at 1300 °C, and subsequently used for the combustion experiments under air and oxyfuel conditions.

2. Materials and methods

2.1. Sample preparation

Biosolid, provided by a waste water treatment facility in Western Australia, was dried overnight in an oven at 105 °C before it was ground

* Corresponding author.

E-mail address: h.wu@curtin.edu.au (H. Wu).

Table 1

Properties of the biosolid size fractions of 38–60 μm , 60–90 μm and 120–150 μm and its respective chars prepared from pyrolysis at 1300 $^{\circ}\text{C}$, which are referred to as small char particle, medium char particle and large char particle, respectively.

Char samples	Moisture (wt%, ad ^a)	Proximate analysis (wt%, db ^b)			Ultimate analysis (wt% daf ^c)			
		ash	VM ^c	FC ^d	C	H	N	O
38–60 μm biosolid	5.5	20.4	68.9	10.6	53.54	10.90	6.79	28.77
60–90 μm biosolid	5.2	20.4	70.5	9.1	53.41	11.02	6.84	28.73
120–150 μm biosolid	4.5	20.2	70.0	9.8	55.08	11.07	7.13	26.72
Small char particle	1.2	84.0	5.2	10.9	98.61	0.15	0.37	0.86
Medium char particle	0.9	84.3	4.7	11.1	99.21	0.11	0.34	0.34
Large char particle	0.6	83.9	5.4	10.7	99.33	0.10	0.40	0.17

^a Air-dried.

^b Dry-basis.

^c Volatile matter.

^d Fixed carbon.

^e Dry and ash free basis.

and sieved to yield three size fractions of 37–60 μm , 60–90 μm , 120–150 μm for the pyrolysis experiments. Table 1 presents the properties of the prepared biosolid.

The pyrolysis experiments were conducted in a drop tube furnace (DTF) described in detail elsewhere [15]. Briefly, the DTF was preheated to 1300 $^{\circ}\text{C}$, and then samples of the three biosolid size fractions were in turn entrained by 1 L/min of ultra-high purity nitrogen into the DTF through a water-cooled feeding probe using a sample feeder system. An additional stream of 1 L/min of nitrogen was used to prevent backflow of the volatiles. The char produced was sampled using a water-cooled sample probe. A stream of 1 L/min of helium was injected at the probe tip to quench the hot flue gas, while extra nitrogen was introduced to give a total gas flow of 10 L/min before the char particles were collected in a Dekati cyclone. Henceforth, the biosolid chars prepared from pyrolysis of the biosolid size fractions of 37–60 μm , 60–90 μm and 120–150 μm are termed as small, medium and large char particles, respectively. Fig. 1 shows the cumulative particle size distribution of the three biosolid chars, and Tables 1 and 2 show their main properties.

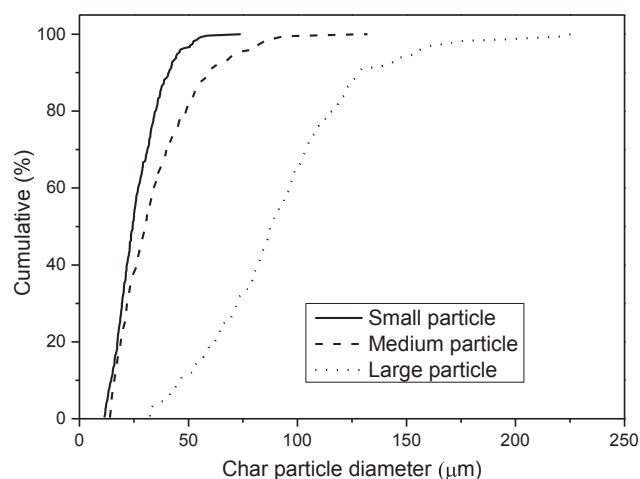


Fig. 1. Cumulative particle size distribution of the three biosolid chars.

Table 2

Inorganic elements content of the biosolid chars.

	Small char particle	Medium char particle	Large char particle
<i>Major elements (wt%, dry basis)</i>			
Na	0.642 \pm 0.053	0.727 \pm 0.095	0.591 \pm 0.100
K	0.642 \pm 0.016	0.867 \pm 0.010	0.679 \pm 0.018
Mg	5.692 \pm 0.045	4.597 \pm 0.101	3.825 \pm 0.028
Ca	13.486 \pm 0.057	13.470 \pm 0.312	13.007 \pm 0.053
Al	3.323 \pm 0.036	3.460 \pm 0.014	3.753 \pm 0.060
Fe	1.655 \pm 0.034	1.710 \pm 0.024	1.747 \pm 0.007
Si	8.569 \pm 0.030	7.814 \pm 0.035	9.056 \pm 0.030
Ti	0.797 \pm 0.004	0.973 \pm 0.024	1.022 \pm 0.008
P	11.649 \pm 0.160	11.574 \pm 0.252	9.502 \pm 0.030
S	0.204 \pm 0.002	0.220 \pm 0.002	0.298 \pm 0.002
<i>Trace elements (mg/kg, dry basis)</i>			
As	4.075 \pm 0.091	4.041 \pm 0.028	3.312 \pm 0.477
V	27.501 \pm 0.120	34.141 \pm 3.943	31.402 \pm 4.346
Cr	273.921 \pm 36.0	207.1 \pm 16.7	344.9 \pm 47.5
Co	21.748 \pm 0.258	25.181 \pm 2.822	19.389 \pm 1.295
Cd	2.045 \pm 0.030	2.046 \pm 0.087	1.617 \pm 0.188
Pb	7.607 \pm 0.109	6.789 \pm 3.395	8.404 \pm 1.049
Zn	659.925 \pm 16.4	697.165 \pm 4.8	545.563 \pm 12.5
Mn	523.917 \pm 13.8	522.624 \pm 3.1	545.388 \pm 17.2
Cu	1755.5 \pm 37.4	1778.0 \pm 10.3	2131.5 \pm 50.8

2.2. Char combustion experiments

The biosolid char combustion experiments under air and oxyfuel (30% O₂/70% CO₂) conditions were carried out in a DTF equipped with a sampling system that comprises a cyclone and a 13-stage Dekati low-pressure impactor (DLPI) coupled with a backup filter [14,16]. During the char combustion experiments, \sim 0.03 g/min of each char, entrained in a stream of 1 L/min of air or oxyfuel gas, was fed into the DTF at 1300 $^{\circ}\text{C}$. A second flow of 4.6 L/min of air or oxyfuel gas was introduced in the DTF to assist the char combustion process. The value of λ (expressed as the ratio of the actual air/fuel ratio to the stoichiometric air/fuel ratio) was \sim 30 and the residence time of the char particles in the isothermal zone of the DTF was \sim 1.2 s. The sampling temperature was set at 115 $^{\circ}\text{C}$ in this study. The ash and PM particles with aerodynamic diameter of $>$ 10 μm were first removed from the flue gas by the cyclone, and then the flue gas was directed to the DLPI for size-segregated collection. In this study, PMs with aerodynamic diameters $<$ 0.1 μm , 0.1–1 μm , $<$ 1 μm , 1–10 μm and $<$ 10 μm are termed as PM_{0.1}, PM_{0.1–1}, PM₁, PM_{1–10} and PM₁₀, respectively. All experiments were carried out at least in triplicates. It should be noted that complete combustion was achieved for all combustion experiments as thermogravimetric analysis showed the absence of unburned carbon in the PM samples, and total organic carbon analysis showed that leachates from washing PM samples in pure water for 24 h contained negligible amounts of organic carbon.

2.3. Sample analysis

The proximate analysis of the biosolid chars was carried out in a thermogravimetric analyser (TGA, Mettler Toledo Star 1) according to the time-temperature program described in ASTM E870-82. The C, H and N contents were determined by an elemental analyser (PerkinElmer 2400 CHNS/O Series II). The sulphur content in the biosolid chars were determined by an improved Eschka method [17]. The quantification of the contents of major (Na, K, Mg, Ca and P) and trace (As, Cr, Cu, Mn, Pb, Ti, and Mn) elements were made by using inductively coupled plasma-optical emission spectroscopy (ICP-OES, PerkinElmer Optima 8300) and inductively coupled plasma-mass spectroscopy (ICP-MS, PerkinElmer NexION 350D), respectively, with the biosolid chars being first ashed and then digested in a concentrated HNO₃/HF mixture (detailed procedure described elsewhere [18]). Likewise, the major and trace elements in PM were also quantified using ICP-OES and ICP-MS,

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