JOURNAL OF ENVIRONMENTAL SCIENCES 42 (2016) 246–258

Available online at www.sciencedirect.com

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www.journals.elsevier.com/jes

JES JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

Emissions from the combustion of eucalypt and pine chips in a fluidized bed reactor

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A R T I C L E I N F O

Article history:
Received 16 May 2015
Revised 18 July 2015
Accepted 20 July 2015
Available online 1 October 2015

Keywords:
Biomass
Combustion
Fluidized bed
$PM_{2.5}$ emissions
Chemical composition

A B S T R A C T

Interest in renewable energy sources has increased in recent years due to environmental concerns about global warming and air pollution, reduced costs and improved efficiency of technologies. Under the European Union (EU) energy directive, biomass is a suitable renewable source. The aim of this study was to experimentally quantify and characterize the emission of particulate matter ($PM_{2.5}$) resulting from the combustion of two biomass fuels (chipped residual biomass from pine and eucalypt), in a pilot-scale bubbling fluidized bed (BFB) combustor under distinct operating conditions. The variables evaluated were the stoichiometry and, in the case of eucalypt, the leaching of the fuel. The CO and $PM_{2.5}$ emission factors were lower when the stoichiometry used in the experiments was higher (0.33 ± 0.1 g CO/kg and 16.8 ± 1.0 mg $PM_{2.5}$/kg, dry gases). The treatment of the fuel by leaching before its combustion has shown to promote higher $PM_{2.5}$ emissions (55.2 ± 2.5 mg/kg, as burned). Organic and elemental carbon represented 3.1 to 30 wt.% of the particle mass, while carbonate (CO_3^{2-}) accounted for between 2.3 and 8.5 wt.%. The particulate mass was mainly composed of inorganic matter (71% to 86% of the $PM_{2.5}$ mass). Compared to residential stoves, BFB combustion generated very high mass fractions of inorganic elements. Chloride was the water soluble ion in higher concentration in the $PM_{2.5}$ emitted by the combustion of eucalypt, while calcium was the dominant water soluble ion in the case of pine.

Introduction

The growing interest in developing alternatives to fossil fuels has led the scientific community and other decision makers to consider other sources of energy (Brunner et al., 2009; Khan et al., 2009; McKendry, 2002; Obaidullah et al., 2012; Vamvuka and Sfakiotakis, 2011). The use of renewable energy sources will become more important as the reserves of fossil fuels become smaller. The renewable energy sources increase the possibilities for self-sufficiency and can play an important role in reducing the greenhouse gas emissions (Nussbaumer, 2008; Saidur et al., 2011). Under the European Union (EU) energy directive, biomass is an eligible renewable source. The development of competitive biofuel conversion technologies

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http://dx.doi.org/10.1016/j.jes.2015.07.012

with high conversion efficiency, low emissions, and with low operating cost is a challenge (Hustad et al., 1995). Among the technologies available, bubbling fluidized bed combustion (BFBC) is one of the most advantageous. This technology applied to biomass represents an important asset in many industrial processes and is a practical approach for increasing bioenergy use, because it presents several advantages that include high efficiency, fuel flexibility and low environmental impact (Koornneef et al., 2007; Obernberger and Dahl, 1998). Furthermore, this technology also allows a high rate of heat and mass transfer, low pressure drops, and uniform temperature distribution (Anthony, 1995; Werther et al., 2000). BFBC is a technology with high versatility that can be used for burning a very broad range of solid fuels (Anthony, 1995; Calvo et al., 2013; Duan et al., 2013; Kowarska et al., 2013; Leckner et al., 2004; Tarelho et al., 2011; Xie et al., 2007).

Despite the advantages, attention must be paid to operating and environmental problems. There are several factors that can influence operating conditions. The choice of biofuel depends on the option for the conversion process (McKendry, 2002). Plants depend on fundamental processes for growth (Jenkins et al., 1998) that have influence on its chemical characteristics and thus on the emission profiles. Solid biofuels present chemical elements in different concentrations depending on the type and origin of biomass (Obernberger et al., 2006). The chemical composition of biofuels is related to the composition of the soils and with the type of plant species, because different species will take up different compounds from the soil at different extents. The main problems derived from the biofuel chemical composition are related to ash produced during the combustion process. These problems comprise bed agglomeration, slagging, fouling and corrosion (Arvelakis et al., 2001; Hand and Kreidenweis, 2002; Nussbaumer, 2003; Silvennoinen and Hedman, 2013; Spliethoff et al., 2000). Elements like Si, K, Na, S, Cl, P, Ca, Mg, and Fe are involved in reactions leading to ash fouling and slagging. K and Cl are easily volatilized at high temperatures and condense in the convective section, contributing to corrosion, or are emitted as aerosols. Potassium can lead to K silicate formation with low melting points, causing slagging and bed agglomeration (Van Loo and Koppejan, 2008). The characteristics of the ashes may also limit their subsequent use (Hand and Kreidenweis, 2002; Nussbaumer, 2003; Silvennoinen and Hedman, 2013; Spliethoff et al., 2000). BFBC technology helps preventing some ash related problems as a result of the relatively low uniform temperature and good mixing of bed material (Armesto et al., 2002; Vamvuka et al., 2009; Yan et al., 2005). Biomass leaching is an option that can contribute to minimize some operating problems related either to alkali metals (*e.g.* K and Na), or to other elements, such as chlorine and sulfur. Increasing the ash fusion temperatures allows to reduce the ash related problems like bed agglomeration and deposit formation during combustion (Arvelakis et al., 2001; Bakker et al., 2002; Jenkins et al., 1996; Vamvuka and Zografos, 2004). Particles resulting from biomass combustion are composed of soot, organic and inorganic matter. Operation under stable and efficient conditions generates particulate emissions composed mainly of inorganic compounds. The environmental and health effects of particulate matter are dependent on its physical and chemical properties. Although good combustion conditions lead to lowest particulate emissions, several studies have reported highest oxidative stress, inflammatory, cytotoxic and genotoxic activities and decreased cellular metabolic activity from particles generated under efficient combustion conditions rather than particles resulting from inefficient combustion (Happo et al., 2013; Uski et al., 2014). The size of the particles generated during combustion is a very important factor. Ultrafine particles (particle diameter < 100 nm) are particularly harmful to human health, because they have a sufficiently small size to penetrate the membranes of the respiratory tract and enter the bloodstream or be transported by the olfactory nerves to the brain (Pöschl, 2005). Hata et al. (2014) found that particles resulting from biomass combustion have a mass that fell within a range of <100 nm and those particles smaller than 0.43 μm contribute greatly to the total levels of toxic polycyclic aromatic hydrocarbons (PAHs) and water-soluble organic carbon (WSOC).

Studies have shown that BFBC technology has high flexibility to burn a large variety of fuel combinations, while still achieving low levels of pollutant emission (Ghani et al., 2008; Khan et al., 2009). However, gaseous and fine particulate matter emissions have been considered hazardous to human health and control devices are not effective in the elimination of pollutants from the flue gas (Yao et al., 2010; Ye et al., 2012). Taking into account the environmental and human health impact of these emissions and the need to improve operating conditions, a detailed quantification and characterization of emissions is necessary. Although several studies about BFBC of biomass have been developed along the years, the environmental aspects of the technology related to flue gas emissions have been overlooked. As far as we know, only Calvo et al. (2013) have chemically characterized particle emissions from the co-combustion of forest biomass and sewage sludge in a BFBC. In this study, gaseous and particulate emissions from the combustion of pine and eucalypt chips in a pilot-scale BFBC were studied, taking into account operating aspects such as stoichiometry and biomass pre-treatment by leaching. In 2006, the Portuguese government has decided that the production of electricity from combustion plants dedicated to biomass should be 250 MW in 2020 (Teixeira, 2012). The purpose of this research is focused on fulfilling the need of detailed chemical characterization of emission profiles resulting from fluidized bed units, which represent a substantial fraction of the current installed capacity of electricity generation from biomass. In addition to being useful to define the best operating conditions, chemical fingerprints of emissions are needed to: (i) run regional source apportionment models, (ii) improve inventories, (iii) apply air quality models, and (iv) assess potential health effects in the exposed population.

1. Materials and methods

1.1. *Fluidized bed combustor*

The experimental part of this work was carried out in a pilot-scale combustion installation with a BFBC (Tarelho et al., 2011; Teixeira et al., 2012; Calvo et al., 2013). The infrastructure is constituted by three main components, namely, the reactive system, the sampling and gas analysis system and the control and data acquisition system (Fig. 1). The reactive system is composed of an insulated pilot-scale fluidized bed reactor made in stainless steel (AISI 310 SS). The bottom bed,