Characteristics and synergistic effects of co-combustion of carbonaceous wastes with coal

Sermin Onenc [a], Stefan Retschitzegger [b], Nikola Evic [b], Norbert Kienzl [b], Jale Yanik [a,*]

[a] Faculty of Science, Department of Chemistry, Ege University, 35100 Bornova, Izmir, Turkey
[b] BIOENERGY 2020+ GmbH, 8010 Graz, Austria

ABSTRACT

This study presents combustion behavior and emission results obtained for different fuels: poultry litter (PL) and its char (PLC), scrap tires (ST) and its char (STC) and blends of char/lignite (PLC/LIG and STC/LIG). The combustion parameters and emissions were investigated via a non-isothermal thermogravimetric method and experiments in a lab-scale reactor. Fuel indexes were used for the prediction of high temperature corrosion risks and slagging potentials of the fuels used. The addition of chars to lignite caused a lowering of the combustion reactivity (anti-synergistic effect). There was a linear correlation between the NO_x emissions and the N content of the fuel. The form of S and the concentrations of alkali metals in the fuel had a strong effect on the extent of SO_2 emissions. The use of PL and PLC in blends reduced SO_2 emissions and sulphur compounds in the fly ash. The 2S/Cl ratio in the fuel showed that only PLC and STC/PLC would show a risk of corrosion during combustion. The ratio of basic to acidic oxides in fuel indicated that ST, STC and STC/LIG have low slagging potential. The molar $(Si + P + K)/(Ca + Mg)$ ratio, which was used for PL, PLC and PLC containing blends, showed that the ash melting temperatures of these fuels would be higher than 1000 °C.

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1. Introduction

Combustion is the most broadly used waste-to-energy technology. Co-combustion of coal with biomass, scrap tires and other carbonaceous wastes is a useful way for recovering energy from wastes and also facilitates waste disposal, air pollution reduction and increases energy security. The advantages of co-combustion have been highlighted by several researchers (Sondreal et al., 2001; Baxter, 2005; Stelmach and Wasielewski, 2008). Meanwhile, co-combustion of coal and wastes has some disadvantages. These are: (1) pre-treatment is needed to convert the waste into a densified solid fuel, (2) higher corrosion risk in case of wastes with high chlorine content, (3) slagging and fouling in the boiler due to the large amounts of alkali metals in wastes. Most studies related to co-combustion are concentrated in the laboratory using thermogravimetric analysis measuring the combustion characteristics or emission characteristics and ash melting characteristics through combustion of coals and different biomass/wastes (Ahn et al., 2014; Toptas et al., 2015; Wu et al., 2013).

The generation of scrap tires in the world is estimated with 13.5 million tonnes per year (Genan Holding A/S, 2017) and scrap tire recycling is a global issue. Today, a large share of the scrap tires in the world end up being incinerated in cement kilns, or disposed of in landfills or civil engineering operations. Scrap tires are a composite mix of many carbonaceous materials making it a perfect feedstock for energy and chemicals feedstock. Rowhani and Rainey (2016) have comprehensively reviewed the uses of scrap tires as fuel. Scrap tires have high calorific value (~32 MJ/kg), which makes them competitive with other types of fuel. Because of the high temperature (>1200 °C) providing the complete combustion, combustion of scrap tires in cement kilns is environmentally safe. However, in a boiler, temperatures are not as high as in cement kilns. Currently, pyrolysis (at 450–500 °C) is the most recommended alternative for the thermochemical treatment of scrap tires, producing pyrolysis oil, synthetic gas and char (Galvagno et al., 2002). The char contains carbon black and inorganic matter. This solid char may be used as activated carbon or as smokeless fuel. But, a reasonable grade of active carbon production from char is still facing many technical challenges. Interestingly, only one report on combustion of STC has come across in literature (Leung and Wang, 1998), although there are numerous studies on the combustion of scrap tires.

Besides scrap tires, poultry litter is also one of the important environmental issues. The intensive poultry production has given rise to environmental concerns at regional and global scales.

Managing the amount of litter produced from intensive poultry farming is a significant undertaking. Poultry litter contains organic matter (wood shavings or straw, manure, feathers, etc.) that can be converted into energy under certain processing technologies (Kantarli et al., 2016; Taupe et al., 2016). Kelleher et al. (2002) asserted that the use of poultry litter as a fuel is one option for poultry litter management, although it has low calorific value. They reported that the low melting point of the ash produced from combustion is a disadvantage of the process. On the other side, the high calcium content of the ash was representing an advantage leading to the reduction of harmful emissions such as NO_x and SO_x during the combustion process. They stated that fluidized bed combustion can be used for the direct combustion of poultry litter. The possible problems related to combustion residues from poultry litter were discussed by several researchers. The co-combustion of poultry litter with coal and carbonaceous materials is also presented in this literature (Billen et al., 2014a, 2014b, 2014c; Lynch et al., 2013, 2014). The combustion of a blend of poultry litter and peat at a ratio of 1:1 was studied in a fluidized bed combustor (Abelha et al., 2003). A feeding problem was observed due to a humidity of the fuel above 25%. Thermogravimetric analysis was also employed in order to reveal information about the co-combustion behavior of poultry litter/lignite blends (Toptas et al., 2015; Yurdakul, 2016). In a study on the co-combustion of lignite and torrefied poultry litter (Toptas et al., 2015), it was observed that the addition of torrefied poultry litter improved the burnout performance of lignite by lowering the burnout temperature. In another study, the combustion behaviors of poultry litter, lignite and their blends in different proportions were investigated by Yurdakul (2016). A synergistic effect was observed during co-combustion but the extent of synergistic interaction depended on the blend ratio.

Differently from the studies in the literature, in this study, both emissions and ash related problems (slagging and corrosion), which are an important reference for the design calculations of boilers, were investigated for the first time for the chars derived from scrap tires and poultry litter and their blends with lignite.

2. Material and methods

2.1. Materials

The fuels used in this study included scrap tires (ST), char derived from scrap tires (STC), a Turkish lignite-LIG (from the Soma basin, Turkey), poultry litter-PL (broiler litter), char derived from poultry litter (PLC) and their blends. Poultry litter was provided by a local farm. Scrap tires were supplied by a local rubber recycling enterprise. STC and PLC were produced by pyrolysis of ST and PL, respectively, at 500 °C with 10 °C min^{-1} heating rate under N_2 atmosphere.

The fuels were ground to a particle size of less than 250 μm and then dried overnight at 105 °C. The coal/STC, coal/PLC and STC/PLC blends were prepared by physical mixing in the ratio of 1:1 (on dry weight basis). The most relevant properties of the fuels used in this study are listed in Table 1.

2.2. Combustion experiments with TGA

Combustion parameters of fuels used were determined using a thermogravimetric analyser (NETZSCH STA 409 CD) with a sample of 50 mg, approximately. For a test run, the sample was heated from room temperature up to 105 °C and kept at this temperature for 1 h. Then it was heated up to 1200 °C with a heating rate of 20 °C min^{-1} under air flow with a flow rate of 100 mL min^{-1}.

Weight loss and weight loss rate were continuously recorded during the process. Two repetitions were run for each sample.

2.3. Combustion experiments with a lab-scale reactor

The lab-scale reactor consisted of a cylindrical retort (height: 35 cm; inner diameter: 12 cm), which was heated electrically and controlled by two separated proportional–integral–derivative (PID) controllers (Fig. 1). A detailed description of the experimental procedures can be found in the manuscript published by Sommersacher et al. (2012). For a test run, the fuel was put in a cylindrical holder (100 mm height and 95 mm inner diameter). The mounting and vessel for the fuel bed were placed on the plate of a scale. The scale was mechanically separated from the retort by a liquid sealing (synthetic thermal oil: Therminol 66). The scale was used to determine the weight loss of the sample during combustion. The sample was introduced into the preheated reactor which was at 450 °C for section 2 while the section 1 was at 800 °C. Two repetitions were run for each sample.

The following measurements/analyses were performed during each of the combustion test runs: (1) Mass decrease of the fuel over time. (2) Concentrations of flue gas species over time: (i) Determination of CO_2, H_2O, CO, CH_4, NH_3, HCN, N_2O, and basic hydrocarbons was performed with a multi-component fourier transform infrared spectrometer (FTIR) (Ansyco Series 447). (ii) The O_2 and H_2 concentrations were measured with a multi-component gas analyzer (Rosemount NGA 2000). (iii) The amount of total hydrocarbons (C_xH_y) was determined with a flame ionization detector (Bernath Atomic 3005). (iv) The O2 concentration was additionally measured with a wideband λ sensor. (v) Nitric oxides (NO_x) were calculated by the difference (fuel N – (NH_3 + HCN)) (3) Temperature measurements over time: (i) Five thermocouples in the fuel bed (three different heights; NiCr–Ni). (ii) Thermocouples in the gas phase (NiCr–Ni). (4) Analysis of the fuel used and residual ash produced. The data of the fuel analysis and the residual ash analysis as well as the weight measurements of the fuel sample and the ash sample were used to calculate the elemental release to the gas phase. This was performed by calculating the mass balance for every relevant element as well as for the total ash.

2.4. Analytical procedure

Ultimate analysis (determination of C, H, N and S) was carried out using a Vario EL 3 elemental analyzer according to EN ISO 16948. Proximate analysis of fuels was done according to EN ISO 18134 for moisture analysis, EN ISO 18122 for ash and EN ISO 18123 for volatile matter and fixed carbon. Major and minor elements in fuels and ashes were analyzed by inductively coupled plasma–optical emission spectroscopy (ICPOES, Arcos SOP, Spectro) following microwave assisted pressurized total digestion (Multiwave 3000, Anton Paar) with nitric, hydrofluoric and boric acid according to EN ISO 16967 and EN ISO 16968. The analysis of chlorine was carried out according to EN ISO 16994 applying combustion in oxygen atmosphere in a closed combustion vessel in connection with the determination of the caloric value (C200, IKA) and subsequent determination by ion chromatography (ICS 90, Thermo Dionex). Total organic carbon (TOC) and total inorganic carbon (TIC) in ash were determined by temperature fractioning carbon phase analysis following DIN 19539 (RC 612, Leco).

3. Results

3.1. Thermogravimetric combustion analysis

Fig. 2 shows comparatively, the standard combustion stages when the wastes and their chars were subjected to treatment