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Thermal Treatment of Paper Sludge Using Torch Plasma

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Abstract. The thermal treatment of wet paper sludge (WPS) and forestry wood waste (FWW) blends (WFB) was studied. This process is performed in pilot-scale 10 kW torch plasma and designed to investigate the effects of batch feeding of sample and their results on product yields, gas composition and thermal treatment performance are addressed. From the scanning electron micrograph (SEM) spectra, the raw WFB is displaced as long fiber and the construction is complete, however, it become to broken piece after the plasma thermal treatment with ash and small piece of fiber co-existed. Controlled at 873 K of torch plasma reactor, the higher heating value (HHV) of residue increased to 1.26 time of sample and its maximum value reached to 5288 kcal/kg. The production of syngas (CO and H_2) is the major component, and almost 90% of the gaseous products appear in 2 min of reaction time, with relatively high reaction rates. The maximum instantaneous concentrations and the corresponding time of CO and H_2 occur at 195,255 and 227,950 ppmv, respectively, and 0.75 min for 873 K, with 0.5 min sampling interval. For batch operation, the total syngas yield is about 34.32 wt. % (CO of 31.58 and H_2 of 2.74 wt.%) of raw sample, and the mass ratio of residue is 25 wt.%. The residue from the torch plasma thermal treatment is with the inorganic components converted into non-leachable vitrified lava, which is non-hazardous.

Keywords: thermal treatment, torch plasma, syngas, paper sludge, wood waste

1. Introduction

Waste water treatment provides one of the significant sources of solid waste in the paper industry. A proper treatment method of waste solid is in fact fundamental to reduce the environmental impact of the paper production process. The broader application of the activated sludge process (ASP) in waste water treatment for pulp and paper mills together with increased production has amplified sludge management problems. The paper sludge is a terminal product of waste water disposal in paper-making process, it contains not only the short-fiber, but also contains the compositions which are harmful to human health, such as a lot of poorly biodegradable organic matter, nitrogen, phosphorus, chlorine, heavy metal, viruses, odour, pharmaceuticals and hormones, parasitic worm's ovum and pathogenic microorganisms, etc. [1]. The presence of harmful substances may represent a complication in the disposal management strategies. While the yearly residue production has been and will continue to increase in the foreseeable future, the conventional management methods such as landfilling, incineration and beneficial uses have come under stronger public opposition and stricter regulatory pressure [2].

The transformation of sludge waste into energy can be efficiently achieved by applying thermochemical techniques, such as gasification [3], [4], pyrolysis [5], [6] and supercritical water treatment [7]. Some innovative gasification and thermal processes have been developed during the previous decades; one of the most promising gasification technologies are catalytic or non-catalytic, high temperature, steam or steam/O2 and plasma gasification [8]-[14]. The gasification of sludge to produce syngas offers an alternative supply of energy for energy recovery. The syngas has the potential use as a high-quality fuel. Moreover, after purification, it becomes an important source of hydrogen which is important in the context of fuel cell

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technology [15]. Thermal plasma offers some unique advantages for waste or fiber biomass conversion, such as providing high temperature and heating rate, in comparison to conventional thermal process. The high energy-density and temperature associated with thermal plasmas and the corresponding fast reactions provide a potential solution for the problems occurred in conventional gasification or combustion processes as well as the residue reduction and stability [8]-[11].

The aim of this work was to study the feasibility and operational performance of thermal treatment of wet paper sludge (WPS) and forestry wood waste (FWW) blends (WFB) using torch plasma. Thermal treatment experiments were performed using carrier gas of N_2 injected at temperature of 873 K. The treatment was performed using a pilot-scale torch plasma system in nitrogen atmosphere with 10 kW power capacities. The residual materials and non-condensable gases were collected and analyzed employing elemental analyzer, gas analytical instruments, and gas chromatography analyzers with thermal conductivity detector (GC-TCD).

2. Methodology

2.1. Research methods

The pilot-scale apparatus used and the experimental procedures for the torch plasma treatment of WFB are shown in previous study [9]-[12]. A 10 kW torch plasma was used for the thermal treatment purpose. For batch feeding, a sample of known pelletized mass (10 g) was placed on the sample input apparatus for feeding the sample material.

2.2. Sample sources and pretreatment

The WPS used in this study was secondary ASP sludge as the terminal product of waste water disposal in paper-making process of paper plant which is located in Township, Hualien County, northeastern Taiwan. The FWW was collected from plantation which is located in Hualien County, and is managed by the Administration of Forestry Conservation Affairs. The sample of WFB was dried in a recycling ventilation drier for 24 h at 378 K before use. The result of the proximate analysis of WFB was 77.86, 18.79, 1.54 and 1.81 wt.% for moisture, combustibles, fixed carbon and ash, respectively. The contents of C, H, N, S and Cl of dry WFB were 44.36, 5.97, 0.4 and 0.55 wt.%, respectively, and the higher heating value (HHV) dry WFB was 4195 kcal/kg.

2.3. Torch plasma operational procedure

The pilot-scale apparatus used and the experimental procedures for the torch plasma are shown in Fig. 1. The flow rate of carrier gas of N_2 (99.99 %) (Q_N) was adjusted to the desired value, say 10 L min^{-1} at 101.3 kPa (1 atm) and 293 K, and was controlled by a rotameter. For the power supply, the power supply control unit (chopper) (Taiwan Plasma Corp.) of torch plasma reactor was set at specific power (P_L) in the range of 2 - 6 kW for the temperatures (T) from 700 to 1000 K, respectively. P_L for the torch plasma used has a maximum power output of 10 kW. After the ignition by tricker, T can also be adjusted via Q_N or current from chopper (IC). The primary sample feeding system consists of a closed cylinder hopper with upper and lower covers. The hopper has a maximum size of 45 mm diameter and 55 mm length. The dried sample was placed in the hopper that can be enclosed by upper and lower covers. The covers were alternatively opened for feeding. For the easy delivering and feeding, the WFB was pelletized to a cylinder with the pellet size of 10 mm diameter and 20 mm length. The torch plasma converts electrical to thermal energy. The applied high voltage on the electrodes results in electric discharges, which in turn generate the current flowing from the anode (+) to the cathode (−) through the gas passing by. The ignition gas such as N_2 is initially introduced and ignited as the voltage is high enough, forming torch plasma. After the ignition of torch plasma, the carrier gas such as N_2 in then introduced. A certain percentage of its molecules are partially or totally ionized, using the dissipation of resistive energy which also makes the gas sufficiently hot. The ionized N_2 gas is thus in plasma state. The reactor is comprised of a crucible, with 1 L in capacity. Two shells were used for refractory insulation in the reactor with outer and inner layers of 5 and 10 cm thickness which can tolerate the temperatures as high as 1673 and 2073 K, respectively. The plasma was injected from the torch into the reactor. A thermocouple was inserted into the reactor for measuring the surrounding temperature of torch plasma gas. The power supply was controlled via the feedback information from temperature readings. The system was operated under atmospheric pressure of 1 atm. The effluent gas surrounded by cooling water flowed through a rotameter and into a water-cooling bath, and then vented to a quench system and hood. Because the synthesis gas may contain acid gases (such as HCl or SO_2), the water-cooling bath can remove water-soluble components of the off-gas including hydrochloric acid, most oxides of sulfur and suspended fine particles, prior to discharge to the quench system and hood. In order to measure the gas products, a gas chromatography was used for the analysis. For the analysis of gas products, a Thermo Scientific FOCUS GC Gas Chromatograph GC-TCD with a Supelco packing column (60/80 carbonxen-1000, 15 ft long, 2.1 mm i.d.) was used. The operation conditions were set as follows: injector temperature 453 K, detector temperature 513 K, column temperature (following the sampling injection) being held at 513 K for 10 min, helium carrier gas flow rate 30 mL min^{-1} for A and B columns, and sample volume 2 mL. Several duplicate experimental runs were performed in order to get the correct values and standard deviation.

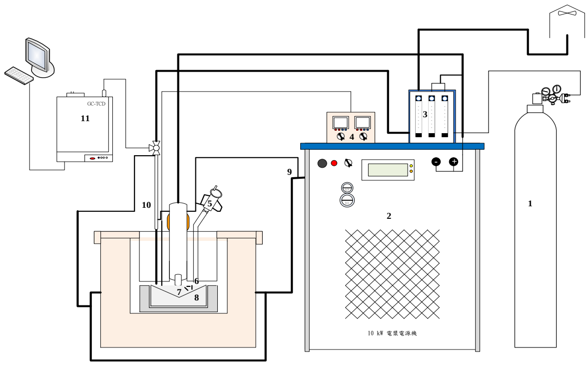
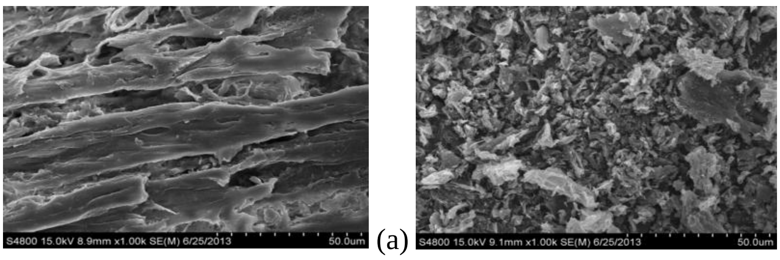


Fig. 1. Schematic diagram of apparatus for the torch plasma.1. Nitrogen cylinder. 2. Power supply chopper and cooling system. 3. Gas flow rate controller. 4. Thermo detector. 5. Sample input apparatus. 6. Sample. 7. Torch plasma and reactor. 8. Crucible. 9. Circulating water pipe. 10. Outlet line. 11. Gas detectors and analytical instruments.

3. Results and Discussion

3.1. Characteristics of raw material and residue

Controlled at 873 K of torch plasma reactor, the higher heating value (HHV) of residue increased to 1.26 time of sample and its maximum value reached to 5288 kcal/kg. The result of the proximate analysis of residue was 73.57, 0.57 and 26.26 wt.% for combustibles, fixed carbon and ash, respectively. Consider the withdraw of moisture content of raw WFB, the result of the proximate analysis was 84.87, 6.96 and 21.73 wt.% for combustibles, fixed carbon and ash, respectively. After the plasma treatment, the both combustibles and fixed carbon were decreased, however, the ash increased. This is reasonable for that the most hydrocarbons were escaped to gas products. The scanning electron micrograph (SEM) spectra were taken for raw WFB and residue, as illustrated in Fig 2. The raw WFB was displaced as long fiber and the construction was complete, however, it became to broken pieces after the plasma thermal treatment. Due to the short reaction time, the residue was still not complete for gasification; ash and small piece of fiber were co-existed.



(a) (b)

Fig. 2. SEM—micrography of raw WFB(a) and residue(b). Scale: x 1000.

3.2. Time distribution in the instantaneous gaseous products

3.2.1. Carbon monoxide and hydrogen (syngas)

The major gaseous products are CO, H_2, CH_4 and CO_2, and they are almost 99 wt.% of all product gas. In previous study [9]-[12], the productions of CO and H_2 are the major components in the gas products with the temperatures yielding the maximum concentrations at 873 K with relatively high reaction rates. Therefore, the temperature was chosen as 873 K in this study. The instantaneous concentrations of CO [CO] and H_2 [H2] in gaseous products at various reaction times ($T_{rsf\text{-}b}$ = reaction time of solid sample in furnace after loading of batch feeding) are shown in Fig. 3a and b, respectively. From Fig. 3a, the maximum instantaneous concentrations and the corresponding $T_{rsf\text{-}b}$ of CO occur at 195,255 ppmv and 0.75 min for 873 K, with 0.5 min sampling interval. Fig. 3b shows that the maximum instantaneous [H2] occur at 0.75 min with [H2] of 227,950 ppmv for 873 K, with 0.5 min sampling interval.

The conversion of C to CO is less vigorous than the formation of H_2 as indicated in Fig. 3a and b with [CO] lower than [H2]. The times for the occurrence of maximum instantaneous concentrations of CO and H_2 are all at the same time, saying 0.75 min. Almost 90% of gaseous products were appeared in 2 min reaction time. Thus, the elevated heating rate of torch plasma allows the reaction reaching the condition with maximum product concentration quickly. Therefore, the torch plasma can be characterized with its elevated energy-density that allows the treatment of solid waste such as WFB faster than the conventional thermal methods. For batch operation, the total syngas yield is about 34.32 wt. % (CO of 31.58 and H_2 of 2.74 wt.%) of raw sample, and the mass ratio of residue is about 25 wt.%.

3.2.2. Methane and carbon dioxide

Fig. 3c shows that the maximum instantaneous concentrations of CH_4 occur at 36,196 ppmv for 873 K at 0.75 min reaction time with 0.5 min sampling interval. After the reaction time of 2 min, the concentration of CH_4 can be neglected. From Fig. 3d, the maximum instantaneous concentrations of CO_2 appear at 14,213 ppmv for 873 K at 0.75 min reaction time. However, the maximum concentrations of CH_4 and CO_2 are far lower than those of the gaseous products of CO and H_2. Shie et al. [10]-[12] pointed out that there are still some other pollutants appearing in the effluent gases, such as SO_2, NOx and HCl, and their maximum instantaneous concentrations are between 2.61 and 11.42 ppmv for plasma pyrolysis of biomass. Therefore, the analysis of these pollutants are neglected and no data shown detail in this study.

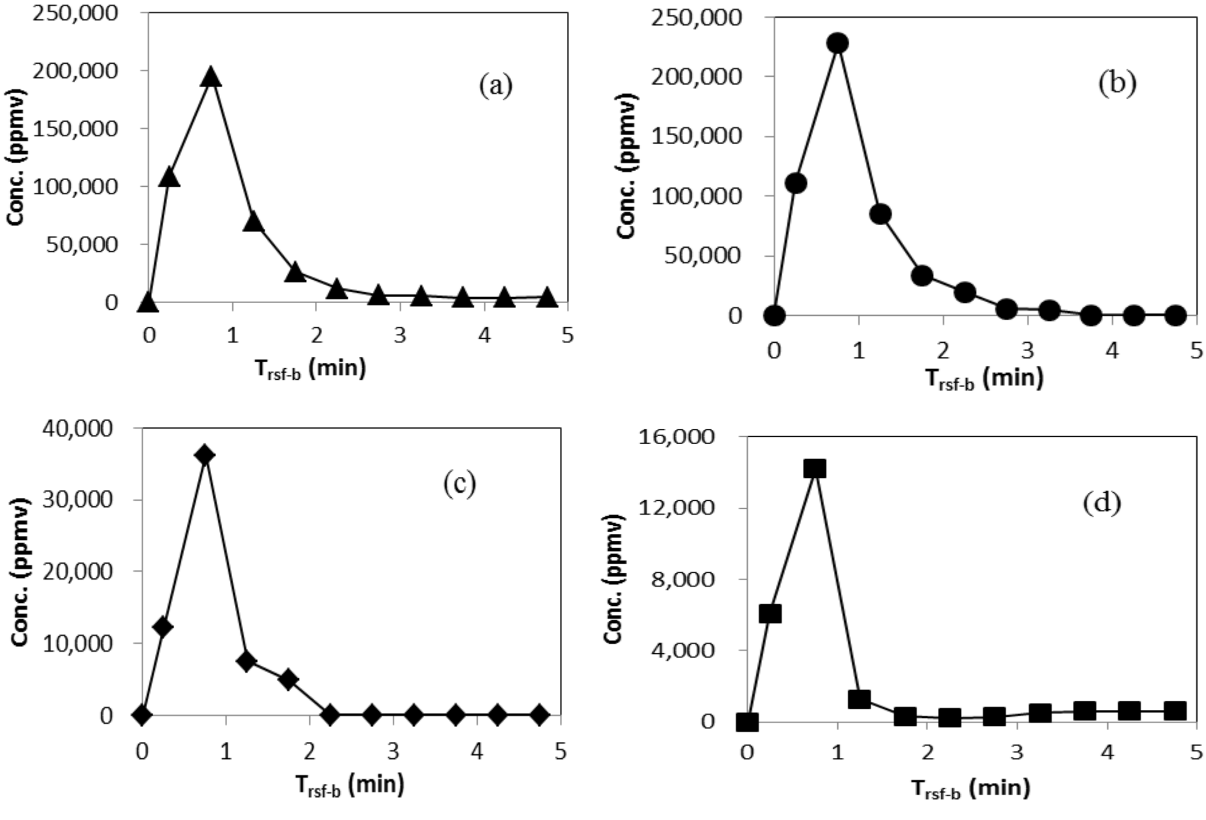


Fig. 3 Instantaneous concentrations in gaseous products from the thermal treatment of WFB using torch plasma. $T_{rsf\text{-}b}$: reaction time of solid sample in furnace after loading of batch feeding. Temperature of reactor = 873 K. (a) CO, (b) H_2, (c) CH_4, (d) CO_2.

4. Conclusion

The thermal treatment of wet paper sludge (WPS) and forestry wood waste (FWW) blends (WFB) was studied. This process is performed in pilot-scale 10 kW torch plasma and designed to investigate the effects of batch feeding of sample and their results on product yields, gas composition and thermal treatment performance are all addressed and discussed in this study. The information is useful for the design of plasma gasification and melting (PGM) process for paper sludge.

5. Acknowledgements

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