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Tar-free fuel gas production from high temperature pyrolysis of sewage sludge

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ABSTRACT

Pyrolysis of sewage sludge was studied in a free-fall reactor at 1000–1400 °C. The results showed that the volatile matter in the sludge could be completely released to gaseous product at 1300 °C. The high temperature was in favor of H_2 and CO in the produced gas. However, the low heating value (LHV) of the gas decreased from 15.68 MJ/N m^3 to 9.10 MJ/N m^3 with temperature increasing from 1000 °C to 1400 °C. The obtained residual solid was characterized by high ash content. The energy balance indicated that the most heating value in the sludge was in the gaseous product.

1. Introduction

Currently, the amount of sewage sludge produced from urban wastewater treatment plants is dramatically increasing in many industrialized countries, and the disposal of waste sludge has been a serious problem facing the whole world (Karayildirim et al., 2006; Domínguez et al., 2008). Owing to more restrictive legislation on the treatment of waste sludge, conventional methods, such as landfill, incineration and agricultural application, with inevitable collateral pollutions have become much less acceptable (Sánchez et al., 2009).

In recent years, pyrolysis, a thermochemical decomposition of organic material at elevated temperatures without the participation of oxygen, has been identified as an effective method to recover the renewable energy from sewage sludge. During the pyrolysis of sludge, the conditions could be optimized to maximize the production of either char, liquid fuel or gas fuel mainly depending on the reactor temperature. Extensive studies had focused on the pyrolysis of sludge for fuel products with the different operating temperature ranges. Inguanzo et al. (2002) investigated the influence of heating rate and final pyrolysis temperature (450–850 °C) on solid, liquid and gas fractions. According to their research, gas fractions produced ranged from 10% to 17%. Sánchez et al. (2009) examined the changes in the composition of the oil obtained from sewage sludge pyrolysis at 350, 450, 550 and 950 °C. They found that gas fractions produced ranged from 20% to 32%. Domínguez et al. (2006a) studied the hydrogen rich fuel gas production from the pyrolysis of wet sewage sludge at high temperature (1000 °C). The results showed that elevated temperature was favorable for obtaining the hydrogen rich fuel gas in processing wet sewage sludge. Others (Inguanzo et al., 2002; Xie et al., 2010; Xiong et al., 2009; Zhang et al., 2011) explored the new method of high temperature pyrolysis using wet sewage sludge. However, little research has been touched upon the pyrolysis of dry sewage sludge for fuel gas at higher temperature (>1000 °C).

In this study, the pyrolysis of sewage sludge was carried out in a free-fall reactor at 1000–1400 °C. Summary results of previous studies and current study was showed in Table 1. It will provide an quick overview of pyrolysis process at <1000 °C and 1000–1400 °C. The effect of reactor temperature on products distribution, gas composition and char property was investigated. The objective was to understand the performance of sewage sludge pyrolysis at high temperature (>1000 °C) and to convert these waste materials to useful and valuable products.

2. Experimental

2.1. Materials

Sewage sludge, produced in Jingzhou urban wastewater treatment plant fed with municipal wastewater, was dewatered by filter press and then collected as original material. The sludge was dried in air at 105 °C for 24 h, and then the dry sample was ground to a size of less than 1 mm for experiments. Table 2 summarizes the proximate and ultimate analyses of the sample. Ultimate analysis of the sample was obtained with a CHNS/O analyzer (Vario Micro cube, Elementar). Such analysis gave the weight percent of

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Table 1
Results of previous studies and current study.

Author	Material	Temperature	Char yield	Oil yield	Gas yield
Domínguez et al.	Wet sludge	1000	32–44.7	3.9–8.5	51.4–62.9
Zhang et al.	Wet sludge	600–1000	≈10	53.9–67.8 (include water)	20–40
Xiong et al.	Wet sludge	700–1000	8.66–11.42	53.55–67.81 (include water)	20.77–39.04
Karayildirim et al.	Dry sludge	500	39.9–41.2	13.2–29.8	14.9–20.9
Díez et al.	Dry sludge	350–550	33–50	30–38	20–29
Present study	Dry sludge	1000–1400	51–53	0–9	37–46

Table 2
Ultimate and proximate analyses of sludge sample.

Moisture	Proximate analysis[a] (%)			Ultimate analysis[b] (%)				
	Volatile matter	Fixed carbon	Ash	C	H	O[c]	N	S
19.5	31.3	7.9	60.8	40.9	6.8	44.2	7.1	1.0

[a] Dry basis.
[b] Dry and ash free basis.
[c] By difference.

carbon, hydrogen, nitrogen, and sulfur in the sample simultaneously, and the weight percent of oxygen was determined by difference. The thermogravimetric analyzer was used to carry out the proximate analysis which was expressed in terms of moisture, volatile matter, fixed carbon and ash.

2.2. Apparatus and procedures

Pyrolysis of sludge was conducted in a free-fall reactor as shown in Fig. 1. The free-fall reactor consists mainly of a feeder, electric furnace, thermocouple, temperature controller, char collector, filter, condenser, tar collector, flow meter, and vacuum pump. The reactor was a corundum tube with an effective length of 600 mm and an inner diameter of 20 mm. An electrical heater (5 kW) was used to heat the reactor and an S-type thermocouple was inserted in the reactor to record the temperature during the pyrolysis. A screw feeder was situated on the top of the reactor to give the feedstock. Feedstock was continuously fed into the reactor by screw feeder with a 1.2 kg/h of feed rate.

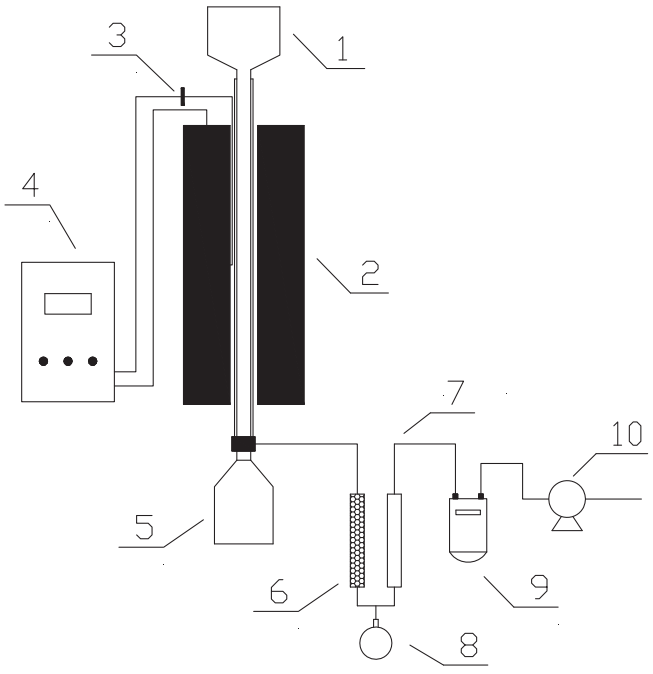

Fig. 1. Experimental apparatus. 1. Feeder; 2. electric furnace; 3. thermocouple; 4. temperature controller; 5. char collector; 6. filter; 7. condenser; 8. tar collector; 9. flow meter; 10. vacuum pump.

Five experimental runs were carried out at reaction temperatures from 1000 °C to 1400 °C in 100 increments. For each experimental run, the reactor tube was heated to a setting temperature. The pyrolysis took place when the feedstock passed through the heated zone of the reactor. The reaction pressure in the reactor was controlled around atmospheric by a vacuum pump. The char was collected in a char receiver. The volatile passed through a metallic filter to remove solid particles and was further cooled in the ice-cooled condenser, where the condensable components were separated. After cooling and purifying, the product gas was sampled and analyzed using a gas chromatography (GC-2000) gas analysis system. Permanent gases such as H_2, CH_4, N_2, CO, CO_2, C_2 (C_2H_4, C_2H_6) were analyzed with Thermal Conductivity Detector (TCD) using 5A, porapak Q and TDX-01 columns. The carrier gas was argon in all analyses. All the experiments were carried out three times, and mean values were used for calculations.

2.3. Methods of data processing

The lower heating value (LHV) of the produced gas is calculated by,

$$\mathrm{LHV\ (kJ/N\ m^3)} = (\mathrm{CO} \times 126.36 + \mathrm{H_2} \times 107.98 + \mathrm{CH_4} \times 358.18 + \mathrm{C_2H_4} \times 590.36 + \mathrm{C_2H_6} \times 637.72) \quad (1)$$

where CO, H_2, CH_4, C_2H_4 and C_2H_6 are the molar percentages of components of the product gas.

The carbon conversion efficiency is calculated by,

$$X_C\ (\%) = [12Y(\mathrm{CO\%} + \mathrm{CO_2\%} + \mathrm{CH_4\%} + 2 \times \mathrm{C_2H_4\%} + 2 \times \mathrm{C_2H_6\%})/(22.4 \times \mathrm{C\%})] \times 100\% \quad (2)$$

where Y is the product gas yield (N m^3/kg), C% is the mass percentage of carbon in ultimate analysis of the sample, and the other symbols are the molar percentage of components of the product gas.