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Energy recycling from sewage sludge by producing solid biofuel with hydrothermal carbonization

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ABSTRACT

The hydrothermal (HT) conversion has been proposed to produce nitrogen, chlorine free solid biofuel or liquid fertilizer from high moisture and nitrogen content bio-wastes, such as municipal solid waste (MSW), mycelial waste, sewage sludge and paper sludge. However, the energy and economic efficiency of this process has not been fully investigated yet. This work focuses on energy recycling from sewage sludge by producing solid biofuel with HT carbonization, in order to optimize the operating parameters and evaluate the energy efficiency of this fuel production process. The effect of the HT temperature and holding time on the biofuel recovering ratio, calorific value and energy recovery rate was investigated. This evaluation fully considered the effect of the HT conditions, mechanical dewatering, thermal drying, and biofuel recovery ratio. Moreover, the energy consumption of sludge thermal drying was introduced to illustrate the economic efficiency of the HT biofuel production process more intuitively. The results show that the HT biofuel production process was more cost-effective than the conventional thermal drying. The HT temperature was the most important parameter to affect the biofuel properties. The carbon content of solid biofuel kept increasing both with HT temperature and holding time, resulting in an increase in the calorific value of biofuel; whereas, the biofuel recovering ratio α, defined as the mass ratio of solid biofuel to raw sludge, also dropped causing a reduction in the energy recovery rate. After the HT temperature was above 200 °C, the energy recovery rate was around 40%. A moderate condition–HT temperature of 200 °C and holding time of 30 min was suggested to produce solid biofuel from sewage sludge with an energy recovery rate of 50%. Practically, it is better to improve the intensity of mechanical dewatering to remove more water from the HT products in order to improve thermal efficiency.

1. Introduction

Municipal wastewater treatment results in generating huge amount of sewage sludge, which requires proper and environmentally acceptable management before final disposal. The management of municipal sewage sludge (SS) is a difficult and expensive problem to solve for many countries. In China, about 20.76 million tons of SS with a water content of 80% has been produced in 2010 [1]. Moreover, this amount will be much huger at the end of 2015 according to the China's 12th Five-Year Construction Plan for National Urban Wastewater Treatment and Recycling Facilities [2], indicating that the other sludge treatment facilities with a capacity of at least 5.18 million tons dried sludge has to be built to meet the environmental requirements in the following years. In a global context, it is organizationally, technically, and economically hardly possible to prevent or strongly reduce the amount of municipal wastewater because of the rapid urbanization, industrialization, and growth in population [3]. Besides that, the presence of toxic pollutants in municipal wastewater cannot be avoided because a large part of these toxics originates from diffuse sources. Accordingly, it is believed that the sludge output would remain increasing gradually in the coming decades [4], and its quality will not change significantly in the future. SS will therefore remain a permanent waste treatment problem requiring an appropriate solution [5].

Currently, bio-energy is an excellent energy recycling technology with bright prospect, giving its ability to recover energy from waste biomass [1,6,7]. The hydrothermal (HT) conversion, which involves the application of heat and pressure to treat biomass in an aqueous medium, was verified as an effective way to densify the energy content of moist biomass without prior drying [8]. For

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sludge, it aims to disintegrate the sludge and result in the formation and accumulation of dissolved products [9]. During the reaction, solid decomposition was significantly affected by reaction temperature rather than reaction time. Higher temperature resulted in higher solids conversion to solid biofuel [10].

The HT conversion has bright perspective with three main merits: (1) largely improving the dewaterability; (2) dramatically reduction in volume, especially for the municipal solid waste (MSW), sawdust, SS and leaves; (3) energy densification. Energy contents of the solid biofuel from primary SS carbonized at 140–200 °C for 4 h ranged from 21.5 to 23.31 MJ/kg, and kept increasing with carbonization [10]. Liu et al. [11] also stated that the energy densification was increased from 1.34 to 1.66 and 1.33 to 1.55 for coconut fiber and eucalyptus leaves, respectively. The highest energy yield was achieved at the lowest temperature adopted because of the relative high biofuel yield. Lu et al. [12] applied HT to produce powder-like solid biofuel from Japanese MSW, Indian MSW and Chinese MSW, at 220 °C and 2.4 MPa for 30 min with a lab-scale autoclave facility. It is reported that the volume based heating value (HV) of MSW was improved at around 6.4–9.0 times. Similar results were also obtained by deriving the data presented by Prawisudha et al. [13], indicating that this volume based energy density was improved around 4–5 times after the HT pretreatment in a pilot plant. The product was easily dryable to powdery fuel with a moisture content of 10% and an average dry basis (d.b.) HV of 20 MJ/kg, as high as that of the low-grade sub-bituminous coal. Moreover, they also observed that the chlorine content of MSW could be reduced from 10,000 ppm (d.b.) to approximately 2000 ppm (d.b.) resulting from the transformation to water-soluble inorganic chlorine. For the combustion characteristics, it was stated that the blending of HT pretreated MSW improved devolatization properties of coal and lowers the ignition temperature of coal [12,14,15]. He et al. [16] also state that the combustion of solid fuel produced from SS by HT is expected to be easier and more stable than raw sludge because of lower activation energy and pre-exponential factor. The solid fuel is supposed to be clean as about 60% of nitrogen and sulfur within SS can be removed during the HT conversion. Moisture content was found to affect the HT carbonization process; feedstocks with higher initial moisture content resulted in lower hydrochar yield [10].

Most of these works have focused on the feasibility of applying HT to produce solid biofuel [11,13,17–19], the kinetics and mechanism of HT solid fuel formation [10,20], the biofuel' characterization [16,21,22], and the biofuels' combustion characteristics [7,12,14–16]. They have distinctly verified that the HT was an effective pretreatment process to produce clean solid biofuel from waste biomass by controlling the water content without prior drying. However, few of them focused on the energy and economic efficiency of this process by fully considering the HT operating conditions, dehydration performance, consequent thermal drying and biofuel recovery ratio, etc., which are very crucial for process optimization and commercialization of this technology. Therefore, this study mainly investigated on the mass and energy balance of solid biofuel production from SS by HT. The effect of HT temperature and holding time on the biofuel recovering ratio, calorific value of solid biofuel, water removal performance, and energy recovery rate were fully taken into account to evaluate the energy efficiency.

2. Materials and methods

2.1. Experimental procedures

In this study, the dewatered activated sludge with a moisture content of (85.94 ± 0.22)% was taken from a wastewater treatment plant in Japan. Its proximate and ultimate analysis results were shown in Table 1.

Fig. 1 shows a diagram of the HT solid biofuel production process and an elementary diagram of the experimental facilities. During the HT treatment, the sludge pre-mixed with pure water (Wako Pure Chemical Industries, Ltd., Japan) as the mass ratio (wet basis, w.b.) of 2:1 (90 g sludge and 45 g pure water) was loaded into a glass tube with a volume of 500 mL. Subsequently, the glass tube was put into the reactor, which was heated by an electronic heat jacket. After that, the reactor was sealed and the argon with a purity of 99.999% was supplied from a cylinder to the reactor in order to create an oxygen free circumstance. The reactor was then heated up to the target temperature and kept constant for a predetermined period. In this study, the HT temperature and holding time ranged from 180 to 240 °C and from 15 to 45 min, respectively. During the reaction, the mixer was kept stirring with its direction switching every 5 min to ensure the uniformity of reaction temperature in the samples. After finishing the reaction, the heater was turned off and the residual steam was discharged and cooled down with a water condenser. When the pressure and temperature fell down to the atmospheric and room temperature, the products were taken out from the glass tube and then kept in a bottle for further use. The condensed liquid was collected and mixed with the products from the glass tube. Each condition was repeated at least 3 times as the same procedure and the final products were mixed to reduce the experimental error.

To calculate the recovery rate α of the solid fuel, about 60 g (dividing into three group) of the pre-mixed products was directly dried in an oven at 105 °C. And another 140 g was taken out to conduct the mechanical dewatering in order to evaluate the water

Table 1
The ultimate and proximate analysis of the samples.

Items	Raw sludge	180 °C			200 °C			220 °C			240 °C		
		15 min	30 min	45 min	15 min	30 min	45 min	15 min	30 min	45 min	15 min	30 min	45 min
Ultimate analysis (dry ashes free basis, *d.a.f*, %)													
C_{ad}	51.20	52.19	53.20	55.31	55.07	57.44	59.23	59.31	60.00	62.31	61.29	62.62	67.96
H_{ad}	6.64	6.57	6.52	6.69	6.72	6.65	6.68	6.68	6.45	6.29	6.26	5.96	5.71
N_{ad}	8.85	9.08	8.98	9.08	9.29	9.04	7.98	9.03	8.24	8.73	8.95	8.19	8.51
S_{ad}	1.37	1.36	1.39	1.37	1.30	1.26	1.26	1.18	1.19	1.20	1.33	1.29	1.56
O_{ad}[a]	31.94	30.81	29.91	27.55	27.62	25.61	24.84	23.80	24.13	21.47	22.17	21.93	16.25
Proximate analysis (air dry basis, %)													
M_{ad}	0.99	1.45	1.54	1.61	1.11	1.07	0.99	0.81	1.24	0.29	1.02	0.53	0.48
V_{ad}	78.49	74.47	72.52	69.63	71.16	70.37	67.56	68.94	67.36	66.59	64.63	62.40	57.42
FC_{ad}	2.01	2.06	2.77	3.20	3.06	3.19	3.60	3.02	3.79	3.97	5.12	6.66	7.42
A_{ad}	18.51	22.02	23.17	25.56	24.67	25.37	27.85	27.23	26.61	29.23	29.83	30.41	34.68
HV[b]	4497	4374	4546	4645	4518	4725	4747	4717	4786	4748	4746	4816	4821

[a] Calculated from the elements mass balance: O = 100–C–H–N–S.
[b] HV: heating value (kcal/kg).