Energy Conversion and Management 103 (2015) 401–407

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Effects of hydrothermal treatment of sewage sludge on pyrolysis and steam gasification

Jihong Moon [a,b], Tae-Young Mun [a], Won Yang [a,d], Uendo Lee [a,d,*], Jungho Hwang [b,c], Ensuk Jang [e], Changsik Choi [e]

[a] Thermochemical Energy System R&D Group, Korea Institute of Industrial Technology, 89 Yangdaegiro-gil, Ipjang, Cheonan, Chungnam 331-822, South Korea
[b] Department of Clean Technology Engineering, Yonsei University, 50, Yonsei-ro, Seodaemun, Seoul 120-749, South Korea
[c] Department of Mechanical Engineering, Yonsei University, 50, Yonsei-ro, Seodaemun, Seoul 120-749, South Korea
[d] Department of Green Process and System Engineering, University of Science and Technology (UST), 89 Yangdaegiro-gil, Ipjang, Cheonan, Chungnam 331-822, South Korea
[e] Institute for Advanced Engineering, 633-2, Baegam, Cheoin, Yongin, Gyeonggi 449-863, South Korea

ARTICLE INFO

*Article history:*
Received 2 April 2015
Accepted 18 June 2015
Available online 6 July 2015

*Keywords:*
Sewage sludge
Hydrothermal treatment
Pyrolysis
Steam gasification
Lignin content
Methane yield

ABSTRACT

Hydrothermal treatment is a promising option for pretreatment drying of organic waste, due to its low energy consumption and contribution to increasing fuel energy density. In this study, the characteristics of hydrothermally treated sewage sludge were investigated, and pyrolysis and steam gasification were performed with the sludge before and after hydrothermal treatment. The overall composition of product gases from treated sludge was similar to that obtained from steam gasification of wood chips, particularly under high-temperature conditions. In addition, the increase in lignin content of sewage sludge following hydrothermal treatment could help enhance methane yield in product gas during pyrolysis and steam gasification. The findings suggest that hydrothermal treatment is an appropriate method for improving sewage sludge for use as an alternative to biomass and fossil fuels.



## 1. Introduction

Biomass and organic waste have been considered stable substitutes for fossil fuels, constituting attractive options for meeting the increasing demand for renewable energy. Sewage sludge, in particular, has recently been considered a promising renewable resource, and the necessary infrastructure for collection has already been put in place, ensuring a stable supply for large-scale energy systems. In such systems, dried sewage sludge has been used as a main fuel or as a co-combustion fuel, with a consequent increase in demand for dried sewage sludge [1–3].

Although sewage sludge has been widely used for anaerobic digestion, with the residue used as a fertilizer or solid fuel with additional treatments, the methods for utilizing sewage sludge are increasingly being refined in order to reduce the costs and environmental problems, and to extend its applications [4]. Anaerobic digestion has many environmental and energetic advantages, but has disadvantages of long residence time (20–30 days) and low efficiency (30–50%) of organic matter decomposition because lignin content in the sludge is poorly decomposed during the digestion process. Therefore, anaerobic digestion is useful for the production of gaseous fuel, but is not the optimal approach as a high-efficiency method of producing solid fuel. In terms of solid fuel production, hydrothermal treatment is a good option because it is generally more efficient than mesophilic digestion. In comparison with many pretreatment processes, the energy efficiency of hydrothermal treatment can be as high as that of thermophilic digestion [5]. Unlike acid-based pretreatments, it does not require costly corrosion-resistant apparatus; the addition of chemicals; or size reduction of biomass, which could reduce the amount of prehydrolyzate conditioning residues and energy consumption [6]. Another environmental benefit of hydrothermal treatment is that the process produces less organic chlorine [7].

Recently, hydrothermal treatment has been introduced as an emerging dehydration technology to reduce the moisture content of organic wastes, and there is growing interest in the integration of hydrothermal treatment with thermochemical or biological energy conversion processes [8,9]. To use sewage sludge for co-combustion in high-efficiency power boilers, pyrolysis, or gasification systems, an appropriate and effective drying process is needed, because the water content of sewage sludge is typically as high as 90% [10–12]. It has been reported that hydrothermal drying of sewage sludge consumes 30% less energy than conventional

* Corresponding author at: Thermochemical Energy System R&D Group, Korea Institute of Industrial Technology, 89 Yangdaegiro-gil, Ipjang, Cheonan, Chungnam 331-822, South Korea. Tel.: +82 41 589 8574; fax: +82 41 589 8323.

*E-mail addresses:* mjh5635@kitech.re.kr (J. Moon), mty1980@kitech.re.kr (T.-Y. Mun), yangwon@kitech.re.kr (W. Yang), uendol@kitech.re.kr (U. Lee), hwangjh@yonsei.ac.kr (J. Hwang), janges95@iae.re.kr (E. Jang), cschoi@iae.re.kr (C. Choi).

http://dx.doi.org/10.1016/j.enconman.2015.06.058
0196-8904/

drying processes, since evaporative latent heat loss of conventional drying methods incurs an energy cost estimated at 539 kcal per kg of waste [13]. Moreover, the hydrothermal process promotes ionic reaction conditions for sewage sludge and destroys organic cell structures by converting bound water into free water, leading to effective drying. Typically, hydrothermal processes operate at 0.4–2.2 MPa and 250–374 °C, with these being subcritical conditions. High-pressure conditions, necessary for maintaining water in a liquid state, can easily be achieved by increasing reaction temperature [14]. Several previous studies indicated that the porosity of solid products decreases and total organic carbon (TOC) increases with increasing temperature. However, reports on the effect of temperature on solid yields are inconsistent [15–18].

In general, the heating value of sewage sludge dried by hot air decreases due to the loss of light, volatile components during the drying process. However, the hydrothermal process would effectively minimize volatile losses by fixing more organic compounds within the solid product. Furthermore, the liquid product from the hydrothermal process contains organic compounds suitable as a feedstock for anaerobic digestion in biogas production [19,20]. In this study, anaerobic digestion was also tested for the liquid product of the hydrothermal process. The combination of gasification of solid products and anaerobic digestion of liquid product can help improve total energy recovery from sewage sludge.

To observe the influence of hydrothermal treatment on sewage sludge, this study analyzes the properties of sewage sludge before and after such treatment. In addition, pyrolysis and steam gasification of sewage sludge treated with and without hydrothermal processes were conducted in a laboratory-scale tube furnace. Transient yield and composition of gases produced during pyrolysis and steam gasification were monitored over time. Finally, the potential for use of hydrothermally treated sewage sludge in steam gasification as an alternative lignocellulosic feedstock was evaluated by comparing the obtained results with previous results from steam gasification of wood chips.

## 2. Material and methods

### 2.1. Materials and hydrothermal process

The material used for this study was sewage sludge, before and after hydrothermal treatment. Before discussing the properties of the material, the procedure for pretreatment of sewage sludge is explained. Fig. 1 shows a process flow diagram of the hydrothermal treatment and drying process for sewage sludge, including anaerobic digestion of the liquid byproduct and mass balances for each process; it also shows photographs of the products at each stage. This process is able to dry 1 t/d sewage sludge continuously. Details of the hydrothermal treatment system are available in the literature [21]. In this study, the raw sewage sludge received from the initial dehydration process had a moisture content >80 wt.% in its wet, solid state. A continuous reactor was used for hydrothermal treatment and temperature was controlled by indirect heat transfer with heated oils as heat carriers. A mono pump was equipped for continuous feeding of raw sludge, with the operating temperature, pressure, and residence time set at 200 °C, 2 MPa, and 1 h, respectively. Approximately 2% volatile matter was vaporized and 98% slurry was obtained from the hydrothermal process, as shown in Fig. 1. The solid and liquid phases of the slurry were separated via a filter press, with the moisture content of the solid product comprising around 30%. The liquid product was used for anaerobic digestion; 13.2 $m^3$ of methane was produced from 842.9 kg of liquid byproduct. With additional drying of the solid product, 96 kg of solid product with a heating value of about 4300 kcal/kg as obtained from 1 ton of raw sludge. The moisture content was reduced from 84.0 wt.% to 8.1 wt.% through a

**Table 1**
Proximate and ultimate analysis of sewage sludge.

| Sample | Before hydrothermal treatment (Dry) (wt.%) | After hydrothermal treatment (wt.%) |
|---|---|---|
| *Proximate analysis*[a] | | |
| Moisture content | 81.9 (4.3) | 8.1 |
| Ash | 3.6 (19.3) | 26.0 |
| Volatile matter | 14.0 (67.2) | 58.4 |
| Fixed carbon | 0.5 (9.2) | 7.5 |
| *Ultimate analysis*[b] | | |
| Carbon | 52.7 | 56.6 |
| Hydrogen | 6.5 | 8.3 |
| Nitrogen | 6.5 | 9.4 |
| Oxygen | 33.2 | 24.7 |
| Sulfur | 1.0 | 1.1 |

[a] Wet basis.
[b] Dry and ash-free basis.

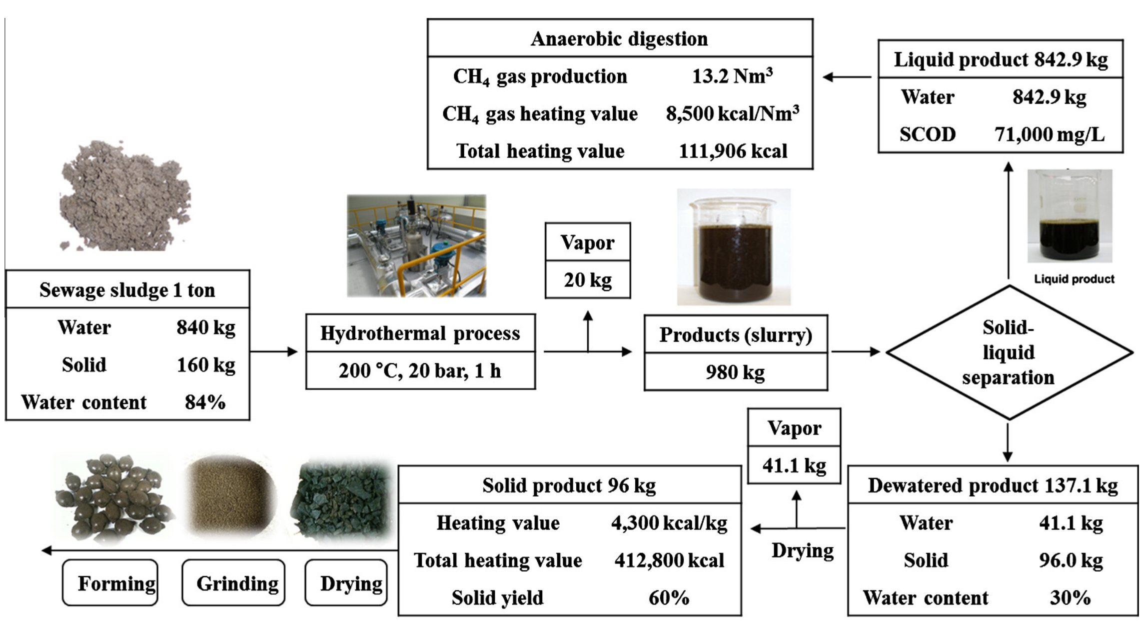


**Fig. 1.** Process flow diagram, mass balance, and photographs of products of the hydrothermal treatment process.