Journal of Environmental Management 203 (2017) 688–694

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Ultra high temperature gasification of municipal wastewater primary biosolids in a rotary kiln reactor for the production of synthesis gas☆

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ARTICLE INFO

Article history:
Received 13 January 2016
Received in revised form
22 February 2016
Accepted 23 February 2016
Available online 3 March 2016

Keywords:
Biosolids
Gasification
Municipal sludge
Primary fine-sieved solids
Waste to energy
Syngas

ABSTRACT

Primary Fine-Sieved Solids (PFSS) are produced from wastewater by the use of micro-sieves, in place of primary clarification. Biosolids is considered as a nuisance product, however, it contains significant amounts of energy, which can be utilized by biological (anaerobic digestion) or thermal (combustion or gasification) processes. In the present study, an semi-industrial scale UHT rotary kiln gasifier, operating with electric energy, was employed for the gasification of PFSS (at 17% moisture content), collected from a municipal wastewater treatment plant. Two gasification temperatures (950 and 1050 °C) had been tested, with minimal differences, with respect to syngas yield. The system appears to reach steady state after about 30–40 min from start up. The composition of the syngas at near steady state was measured approximately as 62.4% H_2, 30.0% CO, 2.4% CH_4 and 3.4% CO_2, plus 1.8% unidentified gases. The potential for electric energy production from the syngas produced is theoretically greater than the electric energy required for gasification. Theoretically, approximately 3.8 MJ/kg PFSS of net electric energy may be produced. However, based on the measured electric energy consumption, and assuming that all the syngas produced is used for electric energy production, addition of excess electric energy (about 0.43 MJ/kg PFSS) is required to break even. The latter is probably due to heat losses to the environment, during the heating process. With the improvement of energy efficiency, the process can be self sustained, form the energy point of view.

1. Introduction

Municipal sludge, known as biosolids, contains significant amounts of energy, which can be exploited by the use of biological or thermal processes (Tchobanoglous et al., 2009; Zhang et al., 2014b). However, the relatively high moisture content of dewatered biosolids (usually over 80%), in conjunction with long industrial experience on anaerobic digestion, make anaerobic digestion the most favorable process for energy production from biosolids. Usually, anaerobic digestion takes place between biosolids thickening and dewatering processes (Gikas, 2008). Anaerobic digestion only partially stabilizes biosolids, while, practically, there is no volume reduction in biosolids during the process. Anaerobicaly digested biosolids contain high amounts of energy, which cannot be further exploited using biological processes (Cao and Pawłowski, 2012). Thus, further processing is required for safe disposal (e.g. lime addition, composting, drying). Biosolids landfilling, even after anaerobic digestion and dewatering, is not a sustainable option, as it is against the direction of recent legislation, which prompts towards the reduction of the landfilling of fermentable organics (European Community, 1999). On the other hand, biosolids drying may not be considered as a complete solution, as dry biosolids tend to absorb moisture, which sooner or later will transform dry biosolids to the initial stage. Finally, composting is not a cost effective process, while the use of compost originated from biosolids is encountered with skepticism from the farmers (Mininni et al., 2014).

Biosolids with relatively high solids content are suitable to undergo thermal processing (combustion or gasification) for treatment and for energy production. Co-combustion with MSW has been practiced extensively, particularly in northern and central Europe (Kelessidis and Stasinakis, 2012), however, it requires the existence of MSW combustion facilities near the wastewater treatment plants. Research is currently performed for the production of small scale biosolids combustors (Neamt et al., 2013), however, the above systems aim to biosolids destruction, rather

☆ 3rd International Conference on Sustainable Solid Waste Management, 2–4 July 2015, Tinos Island, Greece.

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http://dx.doi.org/10.1016/j.jenvman.2016.02.043
0301-4797/

than to energy production. Gasification is a thermal process for the reformation of organic substances, with carbon monoxide and hydrogen, as main products. Carbon dioxide and methane may also be formed in considerable quantities, while trace amounts of hydrocarbons may also be produced (Higman and van der Burgt, 2008). The inorganic fraction of the feedstock is collected as ash (solid residue). The gaseous product of gasification process is known as synthesis gas (syngas). Gasification is a process known since the 17th century (Miller, 2004), however, biosolids gasification has been exploited only relatively recently (Fytili and Zabaniotou, 2008; Fitzmorris and Yinan, 2015). Mass and energy balances indicate that the energy produced during the combustion of the syngas produced from municipal sludge gasification, is usually sufficient to sustain the energy needs of the process. Depending on the type of gasification and on the moisture content of sludge, sludge gasification can be an overall positive energy process. A large variety of types of gasifiers is now commercially available (Higman and van der Burgt, 2008), with gasification temperatures varying from 600 °C (in downdraft gasifiers) up to 1300 °C (in Ultra High Temperature (UHT) gasifiers) (in plasma gasification the operational temperature exceeds 5000 °C). Co-gasification of biosolids and other organic wastes (apart from MSW) has also been exploited (Seggiani et al., 2012; Gikas et al., 2010). Ultra high temperature gasification (above 1000 °C) in the absence of airborne oxygen, results in syngas richer in CO and H_2, with smaller yields of CH_4 and CO_2 (Nipattummakul et al., 2010a; Zhang et al., 2014a), and with relatively minimal production of undesired gases, such as dioxins. The capacity of commercially available gasifiers is generally significantly lower than combustors, which makes the process more appropriate for stand alone operation in wastewater treatment plants (Minguez et al., 2013). Recent studies have shown that the electric energy produced by the gasification of conventional biosolids (at 80% moisture content) can be up to about two times the electric energy produced by anaerobic digestion (Gikas, 2014). The more dry the biosolids, the higher the energy yield of combustion process, while, the optimal moisture content for gasification is between 15–20% (Lumley et al., 2014), as small amounts of water are required to fix the carbon to oxygen ratio. As a result, the more advanced the dewatering process used, the higher the energy yield of the thermal process.

Micro-sieves are novel apparatuses for the removal of solids form raw wastewater through a sieving process, using a rotary fabric belt assembly (cloth openings are between 100 and 350 μm) with continuous solids scraping (Koliopoulos and Gikas, 2013). The removed Primary Fine-Sieved Solids (PFSS) are distinctively different from conventional biosolids (mixture of primary and secondary sludge), as they do not contain cellular mass. They also differ from primary biosolids, as they are collected almost “intact” on the fabric belt, which allows for efficient dewatering through an auger device, producing biosolids with solids content between 40 and 45% (Koliopoulos and Gikas, 2013; Franchi et al., 2012), which is about double, compared with the conventionally dewatered biosolids. PFSS are comprised of tissue paper (cellulose, hemi-cellulose and small amounts of lignin), feces particulate, food waste and fractions of plastics that have passed through headworks bar screens. Biosolids produced by micro-sieves from raw wastewater (PFSS) are more suitable to be used as feedstock for thermal processes, compared with conventionally dewatered biosolids (dewatered through belt filter press or decanter), due to the significantly higher solids content and low concentration of inorganic substances.

The present manuscript aims to study the potential for syngas production from PFSS, using an UHT rotary kiln gasifier. Experiments have been carried out using a continuous mode, semi-industrial scale, gasifier. The composition of Syngas, during the development of gasification process, was monitored online. The overall energy content of the syngas produced has been calculated, and the potential for energy-wise self sustainable operation has been investigated.

2. Materials and methods

2.1. Micro-sieve

An M2 Renewables, Inc, CA, USA, rotary fabric belt sieve (model 1400) with screen openings of 350 μm (Fig. 1a and b), has been used to separate PFSS from raw wastewater. In practice, the working porous size of the belt is significantly smaller, due to solids buildup on the fabric material, which are continuously removed from the top side of the belt and formed at the bottom side, as described below. Solids removal efficiency from wastewater is similar or even higher, compared to primary sedimentation (Koliopoulos and Gikas, 2013; Franchi et al., 2012). A water jet assembly is used for the removal of the solids collected on the belt, while an integral compression auger is used for dewatering (Fig. 1c and d).

2.2. Collection of primary fine-sieved solids

PFSS were collected from the wastewater treatment plant of the city of Adelanto, CA, USA. Adelanto wastewater treatment plant serves approximately 27,000 people, with an average daily inlet flowrate of approximately 15,000 m^3. The PFSS were collected using the above described micro-sieve (Fig. 1), which was equipped with a compression auger, for PFSS dewatering. PFSS chemical and physiochemical characteristics (Table 1) were measured by the Hazen Research Laboratory (Golden, CO, USA). The calorific value of the PFSS was measured as 19 MJ/kg (dry basis). The initial moisture contents of PFSS was 58%, however, the PFSS used for the gasification tests were partially dried to moisture content of about 17% water. Based on elemental analysis, the average ash-free and moisture-free chemical formula for PFSS works out to be $C_{5.0}H_{8.6}O_{3.3}N_{0.147}S_{0.009}$, while if the moisture content (at 17% water) is also taken into consideration, the relative chemical formula is: $C_{5.0}H_{9.68}O_{4.40}N_{0.147}S_{0.009}$. The letter formula indicates that the wet biosolids (at 17% water) has an adjusted C:O molar ratio close to 1:1. Ideally, the molar ratio C:O should be 1:1, to maximize the production of CO, and avoid the production of elemental carbon in the form of soot (C:O > 1) or the production of CO_2 (C:O < 1).

2.3. Description of gasifier

A Semi-industrial scale Pyromex (Germany) Ultra-High Temperature (UHT) gasifier (NEPTUNE, 2010), with maximum capacity 1 ton/d was employed for the gasification of PFSS. The gasifier operates in continuous mode, at temperatures as high as 1400 °C. It comprises of a rotary cylindrical kiln (drum), made of Ni–Cr steel alloy, with internal diameter of approximately 25 cm. Heat is provided by electric energy through heating rods, mounted inside the kiln, parallel to the cylinder axis. The temperature can be controlled within ±2 °C, using a thermocouple mounted at the middle of the drum. A photo of the rotary kiln and the feeding tank (on the right of the reactor) is shown in Fig. 2. Preferably the feedstock material should have a diameter below 2 cm, thus larger pieces should be shredded for size reduction. Then, the feedstock is initially stored into a N_2 purging tank, from where it is conveyed into the feeding tank, and then into the gasifier, at a controlled rate, using an auger device (Fig. 3). Prior to the initiation of the gasification, the feeding tank and the gasification kiln are purged with nitrogen, for the removal of atmospheric oxygen. Controlled supply of small amounts of nitrogen is continued during the operation phase (to