Fuel 111 (2013) 201–210

Contents lists available at SciVerse ScienceDirect

Fuel

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

Hydrothermal carbonization of sewage sludge for energy production with coal

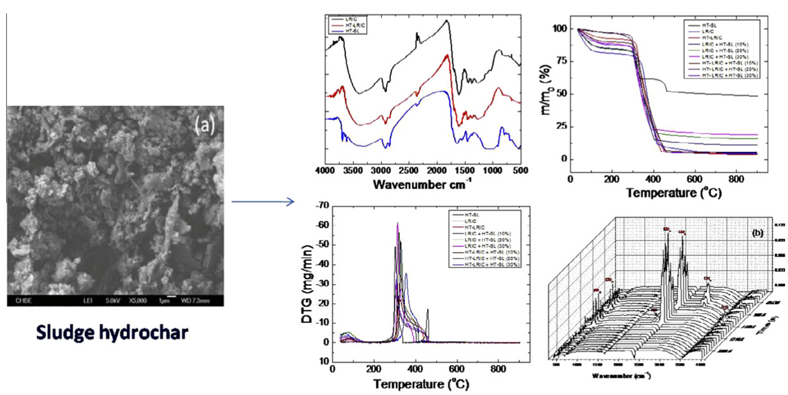
Ganesh K. Parshetti [a,b], Zhengang Liu [a,b], Akshay Jain [c], M.P. Srinivasan [c], Rajasekhar Balasubramanian [a,b,*]

[a] Minerals, Metals and Materials Technology Centre, National University of Singapore, EA Engineering Drive 1, Singapore 117576, Singapore
[b] Department of Civil and Environmental Engineering, National University of Singapore, EA Engineering Drive 1, Singapore 117576, Singapore
[c] Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore 117576, Singapore

HIGHLIGHTS

- Energy rich carbonaceous char was synthesized by HTC of urban sewage sludge.
- The hydrothermally prepared char was characterized by a suite of analytical techniques.
- Co-combustion of upgraded sludge char with raw coal as well as upgraded coal was studied.
- The upgraded char can be used for energy production with minimal greenhouse gas emission.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 28 January 2013
Received in revised form 31 March 2013
Accepted 22 April 2013
Available online 9 May 2013

Keywords:
Hydrothermal carbonization
Fuel
Co-combustion
Sludge char
TGA–FTIR

ABSTRACT

Hydrothermal carbonization using subcritical water (250 °C, 8–10 MPa and 15 min reaction time) was investigated to recover solid carbonaceous fuel i.e. sludge char (HT-SL) from urban sewage sludge. The carbonaceous HT-SL had an energy–density of 15.82 MJ kg^{-1}. For achieving maximum waste-to-energy conversion, the co-combustion of HT-SL with low rank Indonesian coal (LRIC) and hydrothermally upgraded LRIC (HT-LRIC) was investigated using a thermogravimetric analyzer (TGA) and the emission characteristics of gaseous pollutants were determined by using coupled Fourier transform infrared spectroscopy (FT-IR). To gain insights into the physico-chemical and microstructure properties, carbonaceous fuel were characterized by proximate, ultimate, field emission scanning electron microscopy, FT-IR, X-ray diffraction, Brunauer, Emmett and Teller and inductively coupled plasma optical emission spectrometry analysis. Conventional TGA and kinetic parameters such as activation energy of various LRIC, HT-LRIC and HT-SL blends were also determined. This fundamental study provides a basic insight into co-combustion of HT-SL with LRIC and HT-LRIC, which forms a scientific basis for the efficient utilization of sewage sludge as an energy source while minimizing greenhouse gas emissions.

* Corresponding author at: Minerals, Metals and Materials Technology Centre & Department of Civil and Environmental Engineering, National University of Singapore, EA Engineering Drive 1, Singapore 117576, Singapore. Tel.: +65 6516 5135; fax: +65 6872 5483.
E-mail address: ceerbala@nus.edu.sg (R. Balasubramanian).

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.04.052

1. Introduction

In recent years, an increasing awareness of sustainability issues has led to an impetus for efficiency improvement, hazard minimization and utilization of renewable waste resources [1]. Sewage sludge from wastewater treatment plants is a potential energy resource despite containing high levels of pollutants [2,3]. In Singapore, around 80,000 tons of sewage sludge is generated each year from 6 wastewater reclamation plants [4]. In the global context, the amount of sewage sludge generated is expected to increase significantly, considering the rapid population growth, urbanization and industrialization [5]. Various option have been explored in many countries around the world to deal with the accumulation of municipal sewage sludge, including incineration, land filling, land application, road surfacing, conversion to fertilizer, and compression into building blocks [6,7]. However, due to strict environmental and legislative constraints, there is an urgent need for developing more efficient and environmentally friendly approaches for sludge utilization. One of such approaches is to produce solid fuels from sludge through proper pre-treatment, which can reduce dependence on the dwindling supply of fossil fuels while simultaneously solving the environmental problems associated with sludge disposal. Treatment of sludge using hydrothermal carbonization (HTC) can be an attractive alternative to conventional sludge disposal technologies. A number of studies have recently been conducted on HTC covering a wide range of biomass feedstock's (e.g., glucose, cellulose, lignin, and starch), fruit shells, sawdust, rice straw, municipal solid waste, etc. [8–11]. Results from these studies indicated a significant fraction of carbon remains within the hydrothermally prepared char during the HTC process, suggesting production of highly densified fuels and mitigation of greenhouse gas emissions as well. There have been some studies on the hydrothermal treatment of sewage sludge, as reported in the literature. Dote et al. [12] reported on the hydrothermal liquidization of dewatered sewage sludge. The dewatered sludge was liquidized at temperatures above 150–175 °C, and the viscosity of the liquidized sludge was reduced to that of concentrated sludge. Bougrier et al. [13] employed hydrothermal treatment to reduce sewage sludge quantity and improve energy yield using anaerobic digestion. Nges and Liu [14] evaluated effects of hydrothermal pre-treatment on the dewatered-sewage sludge from a municipal wastewater treatment plant in order to improve its biodegradability through anaerobic digestion. Park et al. [2] studied effects of hydrothermally pretreated sewage sludge on the stability and dispersibility of slurry fuel using pulverized coal. Yanagida et al. [15] showed that dewatered sewage sludge (approximately 80% water) was liquidized by hydrothermal treatment in order to make coal–water paste (CWP) for use in a pressurized–fluidized-bed-combustion (PFBC) power plant. Recently, Escala et al. [16] found that HTC of sewage sludge enhanced dewaterability of the sludge, which resulted in a notable lower consumption of energy invested in conventional drying processes. However, there has been no previous systematic investigation on the HTC of sewage sludge for co-combustion with coal and hydrothermally treated coal with real-time analysis of gaseous pollutants. HTC takes advantage of high-moisture contents of sludge feedstock since water is used as the reaction medium under high temperature (250–350 °C) and pressure (5–15 MPa). These conditions produce a highly reactive solvation environment and avoid an energetically costly phase change associated with feedstock drying [9]. Complex biomolecules decompose and reform into a variety of compounds that partition into a self-separating solid phase when conditions return to ambient temperature and pressure.

Recently published reports in the literature have shown that the co-combustion of sewage sludge with coal may be viable from the energetic, economic and environmental points of view, especially when it is carried out in existing infrastructures [17–20]. Co-firing of coal with the sludge is a promising approach to improve the energy output, achieve the environmentally friendly use of coal by reducing greenhouse gas emissions and utilizing waste residues instead of land-filling [21]. However, co-combustion of coal and sewage sludge causes considerable changes in combustion characteristics because the fuel characteristics of sewage sludge differ greatly from those of coal [22,23]. Moreover, the flame may not be stable because of high volatile matter in dried sludge, which may change its combustion profiles [24,25]. Because of these reasons, coal-fired power plants prefer to co-combust coal with sludge that has been carbonized at a low temperature to lower the contents of volatile matter [26–29]. Low-rank coals such as lignite and sub-bituminous coals are frequently carbonized and upgraded by hydrothermal treatment; the upgraded coal by the HTC process has lower moisture and oxygen contents compared with raw coal [30,31]. Several European countries carry out co-combustion of dried and/or dehydrated sewage sludge in coal power plants [32–35]. In order to predict the behavior of carbonized sludge (e.g. hydrothermally prepared char) during co-combustion with natural coal and hydrothermally upgraded coal, it is very important to understand its physico-chemical, structural, thermal and combustion characteristics.

Thermogravimetric analysis (TGA) provides the preliminary knowledge of initial and final temperatures for the combustion of solid fuels as well as other relevant data such as maximum reactivity temperature and char burnout percentage [10,11]. This information can then be used to forecast combustion efficiency, residence time, excess air, boiler design, etc. The use of Fourier transform infrared spectroscopy (FTIR) in conjunction with TGA can provide insights into characterization of gaseous products arising from thermal degradation of various solid materials [4]. In this study, urban sewage sludge was processed through the HTC process to obtain energy densified carbonaceous sludge char (HT-SL) material. Further co-combustion of HT-SL with low rank Indonesian coal (LRIC) and hydrothermally upgraded LRIC (HT-LRIC) was studied with an aim to identify optimal conditions for achieving a maximum waste-to-energy conversion. The physical, chemical, structural and thermal characteristics of carbonaceous fuels were assessed. In addition, a systematic examination of the emission of gaseous pollutants during co-combustion was also conducted using a TGA–FTIR system with different proportions of HT-SL in its blends with LRIC and HT-LRIC.

2. Experimental

2.1. Materials

The secondary sewage sludge from Ulu Pandan (Singapore) sewage treatment plant was collected for this study. The collected sludge (pH: 6.6) was immediately transferred to the lab and stored in a plastic box not beyond 24 h at 4 °C prior to use. LRIC was obtained from a coal mining company in Jakarta, Indonesia. LRIC was manually chopped into small pieces to promote homogeneous mixing and facilitate their effective up-gradation during the HTC treatment.

2.2. HTC: apparatus and procedure

HTC of sludge and LRIC was carried out in a 500 mL Parr stirred pressure batch reactor (model 4575), as shown in Fig. S1 (see Supplementary Information). The HTC study was conducted at a temperature of 250 °C and a pressure of (8–10 MPa) with a constant reaction time of 15 min. In a typical run, 250 ml of sludge and