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Supercritical water gasification of sewage sludge in continuous reactor

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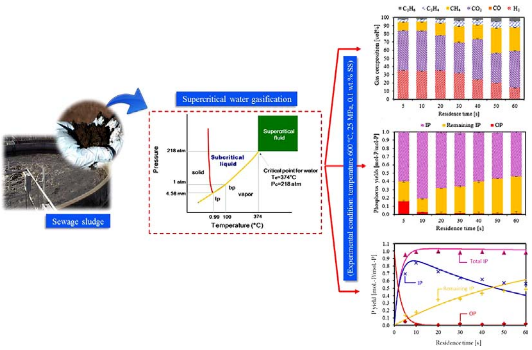
GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a process for the continuous recovery of phosphorus and generation of gas from sewage sludge is investigated for the first time using supercritical water gasification (SCWG). A continuous reactor was employed and experiments were conducted by varying the temperature (500–600 °C) and residence time (5–60 s) while fixing the pressure at 25 MPa. The behavior of phosphorus during the SCWG process was studied. The effect of the temperature and time on the composition of the product gas was also investigated. A model of the reaction kinetics for the SCWG of sewage sludge was developed. The organic phosphorus (OP) was rapidly converted into inorganic phosphorus (IP) within a short residence time of 10 s. The gaseous products were mainly composed of H_2, CO_2, and CH_4. The reaction followed first order kinetics, and the model was found to fit the experimental data well.

1. Introduction

The effort to mitigate climate change has driven increasing research on biomass utilization as an alternative source of renewable energy. Sewage sludge is considered as a promising biomass source for conversion to energy as it contains inorganic matter such as nitrogen and phosphorus and organic compounds such as proteins (± 40%), lipids (10–25%), carbohydrates (14%), and lignins (30–50%) (Goto et al., 1999). Various techniques for converting sewage sludge into useful secondary energy via pyrolysis (Deng et al., 2017; Liu et al., 2017), combustion, and supercritical water gasification (SCWG) have been developed (Han et al., 2017; He et al., 2014; Petzet et al., 2012; Qian et al., 2017; Yanagida et al., 2008). However, sewage sludge has a moisture content of up to 85 wt%, which leads to high drying costs when pyrolysis or combustion is employed. In contrast, SCWG is suitable for converting biomass containing high-moisture compounds such as sewage sludge, as the gasification reaction takes place in water, and pre-drying the biomass is not required (Farobie et al., 2017). Under

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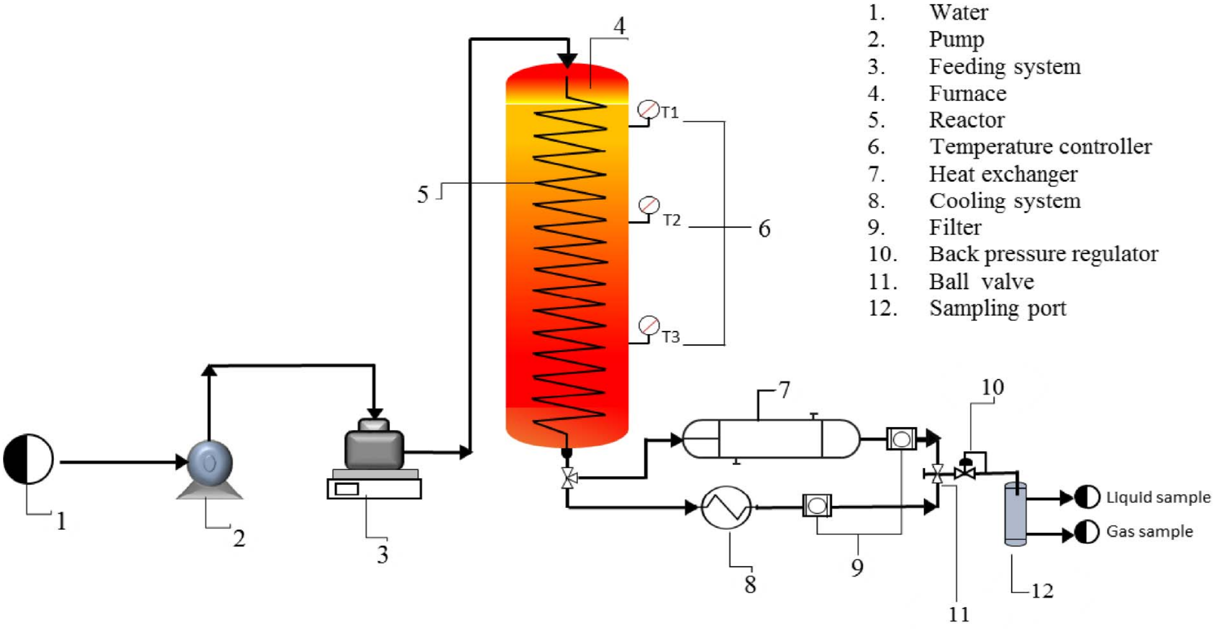

Fig. 1. Experimental apparatus.

these conditions, water has great potential as a solvent for organic components and gases because all of the fluids remain in a single phase (Kruse and Dinjus, 2007; Matsumura et al., 2005; Paksung and Matsumura, 2015; Samanmulya et al., 2017; Yanagida et al., 2008).

Extensive studies on the conversion of sewage sludge into secondary energy using SCWG have been conducted, with focus on gas production. In pioneering studies, Xu et al. (1996) evaluated the SCWG of sewage sludge. Recently, Zhang et al. (2010) reported that supercritical water (SCW) is able to transform sewage sludge into fuel gases such as H_2, CO, and CH_4 with reduced tar and coke formation compared to the traditional thermal processes. Xu et al. (2013) investigated the effect of alkali salts on the direct gasification of sewage sludge in SCW. The hydrogen yield increased in the presence of alkali salts (NaOH, KOH, K_2CO_3, and Na_2CO_3), except for $Ca(OH)_2$. Gong et al. (2016) studied the influence of the reactant composition, i.e., carbon-hydrogen-oxygen, on the key products of the direct gasification of dewatered sewage sludge in a high-pressure autoclave. The total gas production increased with an increase in the C/H_2O ratio of the reactant.

Considering that the recovery of phosphorus from sewage sludge is also important due to the depletion of mineral phosphorus resources, studies on phosphorus recovery from sewage sludge are urgently required. Arakane et al. (2005) recovered phosphorus from excess sludge by applying a process employing subcritical water with magnesium ammonium phosphate (MPA). Yuan et al. (2012) studied the recovery of phosphorus from wastewater through microbial processes, known as enhanced biological phosphorus removal (EBPR). Blöcher et al. (2012) investigated phosphorus recovery from sewage sludge by employing a hybrid process involving low-pressure wet oxidation and nanofiltration. A phosphorus recovery of 54% was obtained in an example of wastewater treatment.

To make sewage sludge treatment energetically efficient, a process for the simultaneous recovery of phosphorus and gas production is needed. A few studies have attempted to recover phosphorus and to generate syngas simultaneously by using SCWG. Thus far, the gasification of dewatered sewage sludge in SCW for energy recovery combined with phosphorus recovery has only been attempted by Acelas et al. (2014). However, a batch reactor was employed in their study. To the best of our knowledge, there are no comprehensive studies on gas generation combined with phosphorus recovery as well as detailed analysis of the reaction kinetics for the SCWG of sewage sludge using a continuous reactor. By employing a continuous reactor, the pressure can be constantly controlled and elucidation of the reaction kinetics is much more precise than in the case of a batch reactor. Therefore, this study aims to investigate the behavior of phosphorus during the SCWG of sewage sludge to determine the effect of temperature and time on the product gas composition and to evaluate the kinetics of sewage sludge conversion under SCWG conditions.

2. Materials and methods

2.1. Experimental

The SCWG of sewage sludge was carried out in a continuous mode reactor. A schematic of the experimental apparatus is shown in Fig. 1. The reactor was made of SS316 steel tubing (i.d. 2.17 mm, o.d., 3.18 mm, and length 12 m). The reactor was placed inside an electric furnace. To start up the experimental setup, water was fed into the reactor. Subsequently, the pressure was adjusted to 25 MPa using a back-pressure regulator. After achieving a constant pressure of 25 MPa, the reactor temperature was set to the desired temperature. The feedstock was then fed using a feeding system at an agitation speed of 400 rpm, with a range of feedstock flowrate of 1.3–15 mL/min. The residence time was changed in the range of 5–60 s. The density of water is 89.74, 78.52 and 70.72 kg/m^3 at the temperature of 500, 550 and 600 °C respectively. After the reactor reached the desired experimental conditions, the feedstock was fed into the system. To ensure steady-state conditions, the reactor was operated for 1 h prior to sample collection. All reaction products were cooled in the heat exchanger, and when a constant gas generation rate was achieved, gas samples were collected in vials and their compositions were determined. Liquid samples were also collected to determine the total organic carbon (TOC) content. All measurements were conducted in triplicate, and the average was taken.

Partial precipitation of phosphorus in the reactor was observed, and the precipitate was recovered after the experimental run. To recover this precipitate, water was fed into the reactor while cooling the reactor, and the effluent generated during this cooling stage was also collected and analyzed.

The residence time was determined using Eq. (1), assuming there was no volume change caused by mixing. The reactor volume here is