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Technical note

Influence of sludge properties on the direct gasification of dewatered sewage sludge in supercritical water

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ABSTRACT

In the present study, ten different types of dewatered sewage sludges were treated in supercritical water in a high-pressure autoclave under a given condition (at 400 °C, 60 min and 23 MPa). The feasibility of direct gasification and the effect of sludge properties on the gasification of dewatered sewage sludge with various properties in supercritical water were investigated. The results showed that dewatered sewage sludge with various water contents (73.48–88.51 wt%), organic matter contents (29.25–73.02 wt %, on dry basis) and inorganics can be directly gasified in supercritical water. The total gas and phenol production increased linearly with the increment of organic matter content in dewatered sewage sludge. The difference in hydrogen content in the gaseous product may be related to the content of water and inorganic as well as pH value of the sludge. The char/coke formed in the solid residue increased with decrement of water content, which inhibited the gasification reaction and resulted in the carbonization reaction.

1. Introduction

Sewage sludge is a complex end-product from wastewater treatment, which is produced in large quantities. Treatment and disposal of waste sludge in an effective and safe way is an important environmental concern in most cities. The best way of sewage sludge disposal is utilization, such as, hydrogen production and compost. Gasification of sewage sludge in supercritical water (SCW) for hydrogen products has been a widespread concern of researchers in recent years [1–3].

Previous studies are focused on concentrated sewage sludge, which contains water up to 95–98 wt%. Xu et al. [4] studied the effect of activated carbon catalyst on the hydrogen yield from sewage sludge samples with 97.2 wt% water content. Xu et al. [5] mixed digested sewage sludge (with a water content of 92.3 wt%) with the corn starch paste for hydrogen rich gas production. Zhang et al. [6] investigated the energy recovery efficiency of secondary pulp/paper-mill sludge (SPP, with a water content of 98.0 wt%) and sewage sludges (with a water content of 95.5–97.2 wt%) in SCW at different temperatures and residence times. However, the volume of concentrated sewage sludge (with a water content of approximately 95 wt%) is four times that of dewatered sewage sludge (DSS, with a water content of approximately 80 wt%). Direct gasification of DSS in SCW can greatly reduce the size of the facility and improve the treatment efficiency. To our best knowledge, few researchers have focused on direct gasification of DSS in SCW.

The properties of sewage sludge vary greatly. In China, wastewaters that are treated in traditional wastewater treatment plant (WWTP) are mostly an mixture of rainwater and domestic wastewater [7], sewage sludge from this WWTP normally contains inorganic substances, including sediment and heavy metals. In addition, the organic materials in sewage sludge vary in content and composition due to differences in wastewater sources and the sewage treatment process. The water content of sewage sludge also varies due to different dewatering processes. Some issues need to be addressed before the practical application of supercritical water gasification (SCWG) of sewage sludge, such as the effect of sludge properties on the gasification of DSS in SCW. Thus, it is necessary to consider whether DSS from different WWTPs can be directly gasified in SCW.

Sewage sludge has a complex nature, which is characterized by high contents of water, organic matter (OM) and inorganic compounds. The OM content and composition affect the yield and

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composition of syngas during biomass conversion in sub- and supercritical water. Kıpçak et al. [8] investigated the partial oxidation of olive mill wastewater in SCW and found that the higher the total organic carbon (TOC) of the feeds (i.e., higher OM content), the higher the total gas production, and the lower the carbon gasification efficiency. Zhang et al. [6] treated SPP and sewage sludge in SCW at 500 °C for 60 min using a Parr high-pressure reactor. The results showed that a higher OM content of sewage sludge resulted in greater gas production for a given quantity of dry sludge and a higher content of heavy oil (mainly phenols). The organic composition also has some impact on the gasification reaction. In addition, the gas composition is slightly changed by alanine addition. Yanik et al. [9] also reported that the yield and composition of gas depend on the organic materials, and concluded that the kind of lignin may also have an effect on gasification products.

Inorganic salts and heavy metals are the main components of inorganic matter in sewage sludge. Inorganic salts, which are insoluble or less soluble under supercritical conditions, can cause plugging of the reactor by precipitation [10]. Moreover, some inorganic salts and metals existed in the sludge have catalytic effects [11]. After the SCWG reaction, the heavy metals in solid products have more stable characteristics [12,13].

The water content also affects the reaction process of biomass gasification in sub- and supercritical water. Xu et al. [14] reported on converting SPP into bio-oils by direct liquefaction in sub- and near-critical water at 280–380 °C. The water content of the SPP was found to decrease from 95.2 to 83.3 wt%, whereas the char yield increased. Zhang et al. [6] also found that a decrease in the water content of the SPP from 98 to 91.2 wt% resulted in a decreased yield of total gas especially significant reductions in the formation of H_2 and CO_2. Susanti et al. [15] investigated the effect of the dry matter content of glucose on gas yield in SCW. A decrease in the water content of glucose from 98 to 85 wt% resulted in a decreased total gas yield. When the glucose content is greater than 20%, large amounts of char/coke are produced which clogs the reactor.

The direct gasification of dewatered sludge in SCW is more attractive because of its higher efficiency during sludge treatment. Consequently, the primary objective of the present work was to study gasified dewatered sludge in SCW (at 400 °C, 60 min and 23 MPa) to determine the feasibility of direct gasification of DSS with various properties in SCW. Moreover, the effects of sludge properties on the gasification of dewatered sludge in SCW were investigated using a batch reactor.

2. Materials and methods

2.1. Materials

In this work, ten different types of DSSs (named S0 to S9) were collected from WWTPs in Jiangsu, China. The locations of the WWTPs and the types of industrial wastewater are shown in Fig. 1. DSS was collected from the WWTPs and stored in the preservation box of a refrigerator at a temperature below 4 °C before experiment. The compositions, in terms of the content of OM, moisture, and ash, as well as ultimate analyses of each type of DSS, are listed in Table 1. The inorganic element composition of each type of DSS is listed in Table 2.

2.2. Experimental apparatus and procedure

The SCWG of DSS was performed in a 316 L stainless steel batch reactor obtained from the Songling Chemical Instrument Co., Yantai, Shandong, China. The schematic presentation of the reactor is shown in Fig. 2. The reactor has a 100-mL capacity and a maximum operating temperature and pressure of 650 °C and 35 MPa,

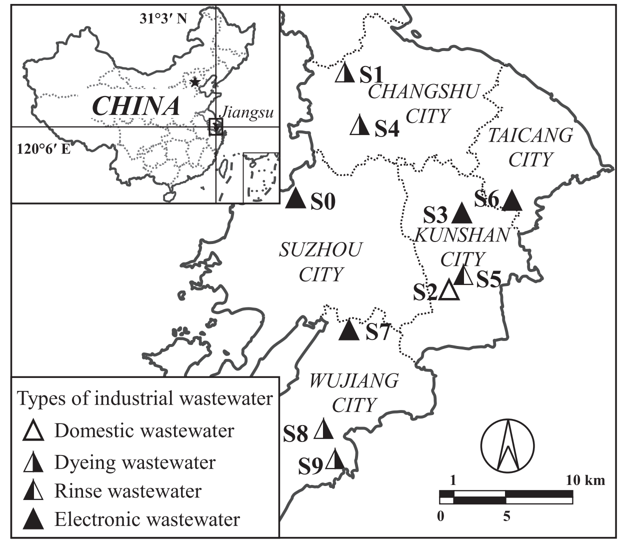

Fig. 1. The locations of wastewater treatment plants and types of industrial wastewater.

respectively. The reactor was heated by a salt-bath furnace, equipped with a PID temperature control unit with a K-type thermocouple. The reaction pressure read from the pressure gauge depending on the reaction temperature and the DSS loading in the reactor, which was not adjusted manually. Our experimental records showed that the reactor pressure was above 22.1 MPa at 400 °C with 33 mL of water in the reactor, indicating that the water reached supercritical conditions at this temperature. The mass of DSS added to the reactor was calculated from the moisture content of the DSS, and the water reached supercritical conditions at 400 °C (i.e., 33 mL).

In a typical experiment, 44 g of DSS (with a water content of 74.8 wt%) was placed in the reactor. Sealed and placed in a salt-bath furnace kept at 400 °C. When the pre-set temperature (400 °C) was reached, it was maintained for a pre-determined residence time (60 min). After that, the reactor was moved from the salt-bath and rapidly cooled to room temperature by water and fans. After cooling, the procedures for sample collection and separation were described in detail in a previous paper [16].

2.3. Product analysis

The method used for analysis of gas, liquid, solid residue and the procedures for char separation and preparation were described in detail in Ref. [16]. The sludge samples were air-dried, pulverized and then sieved under a 100-mesh before analysis. The elemental compositions (C, H, N, and S) of the sludge samples were measured by an elemental analyzer (Vario EL III, Elementar). The inorganic elements (Na, K, Ca, Mg, Fe and Ni) in the sludge samples were determined by ICP–OES (Optima 8000, PerkinElmer). The pH value of the liquid and raw sludge was measured by a pH meter (FE20, Mettler Toledo). Besides, the parameter R_{Liquid} is the ratio of OM residues in liquid, as defined in Ref. [16].

3. Results

3.1. The state of the product after the SCWG

The DSS (S0–S9) used in this study had water contents in the range of 73.48–88.51 wt%, based on the water content demanded to attain supercritical conditions at 400 °C (i.e., 33 mL), we calculated