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Full Length Article

Gasification of dried sewage sludge using an innovative three-stage gasifier: Clean and H_2-rich gas production using condensers as the only secondary tar removal apparatus

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ABSTRACT

Air gasification of dried sewage sludge was performed in a new-type three-stage gasifier consisting of an auger, a fluidized bed, and a tar-cracking reactors. The study aimed to evaluate the possibility of gasification using only condensers for the secondary tar removal method. The effects of Ni- and Fe-impregnated active carbons on the quality of producer gas were also investigated. Finally, to investigate the deactivation behavior of active carbon, a spent active carbon obtained after about 4.3 h of gasification, was used again for approximately 3.7 h of gasification. The active carbons used effectively reduced the contents of condensed and gaseous tars. Ni-impregnated active carbon produced a gas with a high H_2 content (26 vol%) and a low NH_3 content (198 ppmv), while Fe-impregnated active carbon produced a gas with a low H_2S content (96 ppmv). The compositions of the producer gases obtained solely using condensers were similar to those obtained using electrostatic precipitator. During the total ~8 h of gasification, active carbon could efficiently remove tar; however, its surface area and total pore volume slowly decreased with time.

1. Introduction

Due to a rise in global energy demand, attention is focused worldwide on producing renewable energy from various biomass sources. Gasification, a thermo-chemical conversion process, is a technique that has been in use since 1839, when the wood gasifier was built, and has recently been identified as a solution for producing renewable energy from biomass [1,2]. The gas produced from biomass gasification, called producer gas or syngas, can be used as a fuel for heat or electricity generation, or as a feedstock for chemical and fuel synthesis [3]. Biomass gasification is a promising route for H_2 production, because biomass-derived H_2 contributes to renewable energy production [4]. Impurities that evolve during biomass gasification can cause issues that need to be resolved to allow commercialization of gasification processes. For example, tar can result in mechanical problems, such as blocking the pipelines of gasification processing or fouling processing equipment, but it can also deactivate catalysts used during gasification [5,6]. Additionally, tar in producer gas prevents its direct use in gas engines or turbines. Milne and Evans proposed acceptable guideline values for tar content in producer gas for devices, as follows: less than 5 mg/Nm^3 for direct-fired industrial gas turbines, and 50–100 mg/Nm^3 for internal combustion engines [7]. Tar removal approaches are often divided into two methods: primary and secondary. The primary method relies on tar removal inside gasifiers, using tar-cracking additives and/or optimal tar-cracking parameters. The secondary method uses apparatus after gasification, such as a scrubber or an electrostatic precipitator (EP). In addition to tar removal, the secondary method is also effective in removing other impurities (H_2S, NH_3, and HCl) [8]. Currently, most biomass gasification processes that are running or being tested are equipped with a scrubber and (or) an EP. This method, however, poses significant problems when commercialization of a biomass gasification process is considered, because they limit the economic efficiency of the process [9]. Another secondary method is to use catalysts in tar-cracking or reforming reactors. Wang et al. used Ni/char catalysts, and found that the catalysts led to the removal of over 97% of tar at 800 °C and increased H_2 in syngas [10]. These catalysts were also tested for removing tar inside gasifiers [11–13]. Garcia et al. investigated the effect of a Ni-Al catalyst as a fluidized bed material, and concluded that the Ni-Al catalyst enhanced H_2 production and decreased methane content in producer gas [14]. Virginie et al. examined the effect of Fe/olivine, which is inexpensive and non-toxic, on tar removal in a dual fluidized bed biomass gasification process, and concluded that it acted as a catalyst for reforming tar and hydrocarbons [15]. Ko et al. reported that Fe is effective as a sorbent of H_2S between

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Nomenclature

List of abbreviations

BET	Brunauer–Emmett–Teller
CCE	Carbon conversion efficiency
CGE	Cold gas efficiency
DSS	Dried sewage sludge
EP	Electrostatic precipitator
ER	Equivalence ratio
GC-TCD	Gas chromatography-thermal conductivity detector
GC-FID	Gas chromatography-flame ionization detector
ICP-AES	Inductively coupled plasma atomic emission spectrometry
TRE	Tar removal efficiency
UOS	University of Seoul

the temperatures of 500–700 °C [16]. Most catalysts used as primary and secondary methods, however, suffered from deactivation by coke, sulfur, and chlorine [17,18]. Using modified gasifiers as a primary method is very promising, because this does not rely on expensive equipment, like EPs and catalysts. Some approaches reported that modified gasifiers could help overcome the problems associated with tar contaminants, resulting in enhanced H_2-rich syngas yield and process efficiency [19,20].

Our group has developed a staged gasifier (the UOS two-stage gasifier) consisting of a fluidized bed gasifier and fixed bed reactor serially connected, and we conducted a series of gasification of dried sewage sludge (DSS) [21–24]. The two-stage gasifier used active carbon as a tar removal additive, and showed excellent tar removal efficiency with high H_2 production. Recently, a new type of staged gasifier, called the UOS three-stage gasifier, consisting of three serially connected reactors (auger, fluidized bed, and tar cracking reactors), was developed to remove tar more efficiently than the UOS two-stage gasifier. This paper reports for the first time the experimental results of the three-stage DSS gasification, solely using condensers as the primary tar removal method without using any typical expensive tar removal apparatus, such as an EP or a scrubber [25]. This paper also reports the effects of Fe and Ni-impregnated active carbons in the three-stage gasification on the impurity removal (tar, NH_3, and H_2S), and on the H_2 production. In addition, Fe-impregnated active carbon was firstly tested in this paper to reduce the H_2S content in producer gas, and its effectiveness was also provided in detail. Finally, this paper provides results on a long-term gasification (total ~8 h) without any EP and scrubber to observe the deactivation behavior of active carbon and producer gas development, which was the longest operation with DSS in the UOS staged gasifier.

2. Experimental

2.1. Feed material and active carbon

In the experiments, DSS obtained from anaerobic digestion supplied by a wastewater treatment facility in Korea was used. The DSS was first crushed by a disintegrator and sieved to obtain homogenous fractions with diameters ranging between 0.6 and 3.35 mm. The main characteristics of the feed material are presented in Table 1.

Table 1 shows that the DSS contained high nitrogen (~5 wt%) and sulfur (~2 wt%) contents. Nitrogen and sulfur in feed material are the precursors for NH_3 and H_2S liberated during gasification. The DSS had a high ash content (~40 wt%), with Fe, Ca, Mg, and Al as the main metal components. The lower heating value of DSS determined using a bomb calorimeter (Model 6100, Parr) was about 13 MJ/kg. Silica sand was used as the bed material in the fluidized bed gasifier, which had a diameter between 150 and 300 μm. A coal-based virgin active carbon with a size of 1–2 mm and a surface area greater than 1030 m^2/g was used as a tar-cracking additive in the three-stage gasification process. Along with this, metal-impregnated (Ni and Fe) active carbons were also used. The surface areas of the Ni- and Fe-impregnated active carbons, with metal content amounting to ~9 wt%, were approximately 960–980 m^2/g. Metal impregnation was conducted as follows: first, a metal (either Ni or Fe) ion solution was mixed with a coal-based active carbon and stirred. During stirring, the mixture was heated for ~4 h to remove any water content. After heating, the remainder was dried overnight at 90 °C, and then calcined at 400 °C to activate it and remove impurities.

2.2. The UOS three-stage gasification process

A diagram of the three-stage gasification process is presented in Fig. 1.

The three-stage gasifier consists of an auger, a fluidized bed, and tar-cracking reactors, connected serially. The fluidized bed and tar-cracking reactors are separated by a perforated distributor with 1 mm pores. The auger reactor, which is absent from the UOS two-stage gasifier, has a length of 850 mm and an inner diameter of 32 mm and is located in front of the fluidized bed reactor. The auger reactor plays an important role to reduce the tar content in producer gas: it generates a huge amount of tar in advance of the main gasification in the fluidized bed reactor. A portion of the tar generated in the auger reactor can be destroyed through thermal and oxidative thermal decomposition inside the auger reactor. The undestroyed tar leaving the auger reactor can have a long time to react with air used as the gasifying agent inside the fluidized bed reactor, compared to tar directly generated inside a gasifier. The fluidized bed reactor of the three-stage gasifiers, which is the main gasifier, has a height of 390 mm and an inner diameter of 110 mm. Tar can also be produced inside the fluidized bed gasifier by the gasification of rest feed material from the auger reactor and it then enters the tar cracking reactor, which has a height of 410 mm and an inner diameter of 160 mm. The active carbon in the tar cracking reactor absorbs and cracks tar. After gasification in the three-stage gasification process, producer gas can be cleaned by condensers or an EP. Details of the process elements and the operational procedure for the three-stage gasification process have been previously published [26,27].

2.3. Experimental conditions

In all the experiments, the feed rate was 1 kg DSS/h, and gasification time ranged from ~1 to 4.3 h. The amount of silica sand used as the fluidizing bed material was 2.5 kg. Preheated air (~550 °C) was used as the gasifying agent, and the air flow rates for all of the experiments were ~17 Nl/min. The amount of active carbon used, whether it was the virgin or metal impregnated active carbons, was 1 kg. The contact

Table 1
Compositions of dried sewage sludge.

Dried sewage sludge			
Proximate analysis[a] (wt%)		Ultimate analysis[b] (wt%)	
Moisture	7.07 ± 0.31	Carbon	31.32 ± 0.11
Volatile matter	51.53 ± 1.39	Hydrogen	4.56 ± 0.08
Fixed carbon	3.99 ± 0.28	Nitrogen	4.72 ± 0.02
Ash	37.41 ± 1.02	Oxygen[c]	20.72 ± 0.31
		Sulfur	1.27 ± 0.01
Lower heating value[c] (MJ/kg)		13.2	

[a] ASTM E871-82, ASTM E872-82, ASTM D1102-84.
[b] dry basis.
[c] calculated by difference.