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Pressurised gasification of wet ethanol fermentation residue for synthesis gas production

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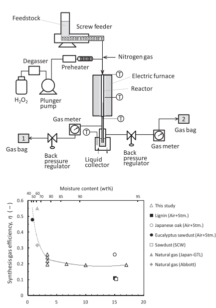
HIGHLIGHTS

- ▶ The pressurised steam gasification of lignin-rich fermentation residue was implemented.
- ▶ The reaction conditions with the highest synthesis gas efficiency were investigated.
- ▶ For the production of BTL synthesis gas, pressurised gasification has the potential to convert residues with above 77.3 wt.% moisture content.

GRAPHICAL ABSTRACT



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ABSTRACT

Pressurised steam gasification of wet biomass in a fixed-bed downdraft gasifier was implemented to identify reaction conditions yielding the highest synthesis gas concentration and efficiency, and to examine the generation of sulphur compounds. The gasification of lignin-rich fermentation residue derived from a bench-plant for bioethanol production from woody biomass was investigated at $p = 0.99$ MPa and $T = 750–900$ °C for steam to biomass ratios (S/B) of 3.4–17 and equivalence ratios (φ) of 3.3–∞. The results showed that the highest concentration of around 70 mol% was obtained at $T \geqslant 850$ °C, $\varphi = 13$ and $S/B = 3.4$, the highest efficiency of 0.26 was obtained at $T = 900$ °C, $\varphi = 3.3$ and $S/B = 3.4$, and sulphur compounds were H_2S and COS. For the production of BTL synthesis gas, pressurised gasification has the potential to convert the wet residue below 77.3 wt.% moisture contents.

1. Introduction

Biomass gasification for the production of synthesis gas ($CO + H_2$) that is utilised for liquid fuel synthesis is a promising technology. The conversion of biomass into liquid fuels has attracted attention because of the growing needs to reduce the use of fossil-based diesel fuels, to develop sustainable energy resources, and to mitigate the amount of carbon dioxide emitted to the atmosphere. The process that produces liquid fuel by the Fischer–Tropsch (FT) reaction of synthetic gas derived from biomass is the biomass-to-liquid (BTL) process. This method, which involves gasification, purification, compression, and FT synthesis (Tijmensen et al., 2002; Hanaoka et al., 2005a, 2010), is a second-generation biofuel production process. Gasification through the BTL process can convert inedible feedstock, e.g., lignocellulosic biomass, into liquid fuels, and does not compete with food production (Zhang, 2010). In an effort to obtain high BTL efficiency, a product

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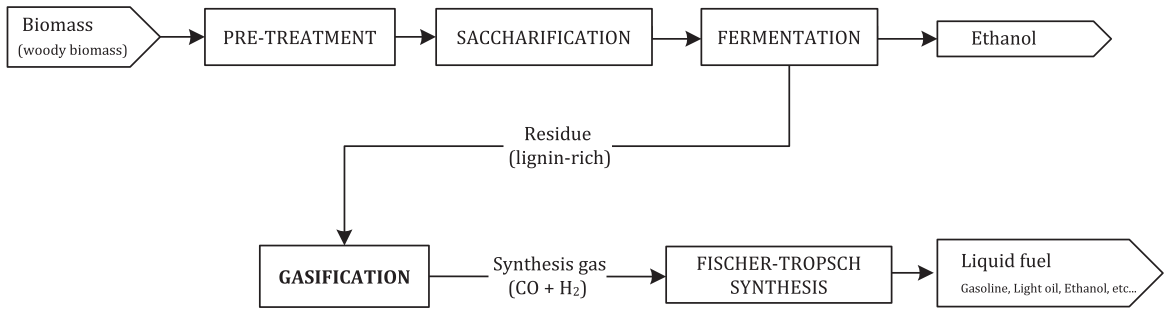

Fig. 1. Integrated woody biomass utilisation system.

gas with a high partial pressure of synthesis gas has been reported (H_2/CO ratio of 2), which was suitable for the Fischer–Tropsch synthesis reaction (Hanaoka et al., 2005a).

Wet biomass, defined as biomass with moisture contents above 80%, has been considered as inappropriate for gasification in terms of its high total-energy efficiency. Instead, a drying process to decrease the moisture content of the feedstock is implemented before the gasification process to suppress the input enthalpy required to achieve the reaction temperature. A previous study by Domínguez et al. (2006), using gasification of aerobically digested sewage sludge as wet biomass showed that char and oil yields decreased and gas yields increased in steam gasification with increasing moisture content. Similar results were obtained in the gasification of lignin char, as reported by Fushimi et al. (2003).

Pressurised gasification is of great advantage in the BTL process. The process containing the gasification can save compression energy compared to that comprising atmospheric gasification. In the BTL fuel production system, high pressure condition is necessary for proceeding liquid fuel synthesis reaction (e.g., 0.1–8 MPa for FT synthesis oil, 5–15 MPa for methanol synthesis, 3–10 MPa for dimethyl ether). The compression energy for the biomass feedstock is smaller than for the product gas, because a larger specific volume requires a larger compression energy. The BTL process with atmospheric steam gasification, compression, FT synthesis, distillation, and hydrocracking requires a compression energy that is half of the total energy input, as described in the simulation results by Fujimoto et al. (2008). Decreasing the compression energy input is an important issue. Also, it would be possible to downscale the gasifier volume for a pressurised gasifier. The residence time of the product gas in the gasifier increases with increasing pressure because the volume of the product gas decreases with the augmentation of pressure. For instance, the residence time of the product gas at 1 MPa is ca. 10 times as long as that at atmospheric pressure at the same temperature and gasifier volume.

Supercritical water gasification (SCWG) as a gasification technology for the conversion of wet biomass is under development. The gasification processes that occur above the critical point of water (p = 22.1 MPa, T = 374 °C) do not require the input of energy corresponding to the latent heat of water. However, it is difficult to maintain the CO concentration of the product gas and control the H_2/CO ratio at 1–2 by means of SCWG technology. The conversion of wet biomass produces low CO concentrations, because the water–gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$) proceeds rapidly (Matsumura et al., 2005; Fiori et al., 2012). Moreover, SCWG of lignin gives low yields of 10–20%, although char production is reduced (Yoshida et al., 2004).

Carbo-V, a BTL plant with 15,000 tonnes-biofuel/year production, including a 45 MW gasification plant operated by CHOREN Industries in Germany at 0.5 MPa and 550 °C with a steam/oxygen agent, has the expertise to produce synthesis gas and liquid fuel with properties similar to petroleum oil through the subsequent FT synthesis reaction (Zhang, 2010; Dautzenberg and Hanf, 2008). The RENUGAS® process uses a pressurised bubbling fluidised-bed gasifier operated by the Institute of Gas Technology (IGT), which gasifies bagasse at 2.24 MPa and 853 °C (Knight, 2000). These synthesis gas production processes via pressurised gasification were scaled up. However, the feedstock for the gasification was wood biomass with low moisture content (around 15–20% for Carbo-V (Rudloff, 2005) and around 15–25% for RENUGAS® (Craig and Mann, 1996)). The production of synthesis gas from high-moisture biomass requires additional discussion, even for a laboratory-scale experiment.

The Biomass Technology Research Centre (currently, the Biomass Refinery Research Centre) at the National Institute of Advanced Industrial Science and Technology (AIST), Japan, has investigated the production of ethanol through the pre-treatment, saccharification, and fermentation of lignocellulose. The process discharges lignin-rich fermentation residues which are difficult to transform into ethanol (Endo, 2010). From the viewpoint of effective residue utilisation, lignin has been employed as a model substrate in some investigations (Doherty et al., 2011; Bozell et al., 2007). However, few researchers have attempted the gasification of residues derived from actual biomass.

Based on the foregoing discussion, a high-efficiency liquid fuel production process from woody biomass was proposed as shown in Fig. 1. The process involves gasification of high-moisture-content fermentation residues derived from ethanol production. This integrated biomass utilisation process has the potential to improve the efficiency of biomass use, owing to the value added to the residue as synthesis gas. The catalyst used in the FT synthesis presented in Fig. 1 is easily poisoned and deactivated by sulphur compounds in the feed gas (Chaffee et al., 1989). Therefore, data that relates the gasification conditions to the production of sulphur compounds are required to remove sulphur from the process. In this study, reaction conditions for high yields of synthesis gas were investigated through the pressurised steam gasification of ethanol fermentation residues derived from actual biomass fermentation processes. Moreover, the generation of sulphur compounds was examined. Based on the findings, the suitability of this gasification technique for unit operations constituting the BTL process will be discussed.

2. Methods

2.1. Materials

Fermentation residues discharged during the development phase of ethanol production from eucalyptus were dewatered, to produce a dewatered cake with 85 wt.% moisture content. It was difficult to feed the dehydrated cake to the gasifier continuously at high pressure. Therefore, the material was dried at 105 °C until the moisture content was reduced to 5.2 wt.%, and then the