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Fischer–tropsch diesel production and evaluation as alternative automotive fuel in pilot-scale integrated biomass-to-liquid process

Young-Doo Kim [a], Chang-Won Yang [a], Beom-Jong Kim [g], Ji-Hong Moon [b], Jae-Yong Jeong [a], Soo-Hwa Jeong [b], See-Hoon Lee [c], Jae-Ho Kim [d], Myung-Won Seo [d], Sang-Bong Lee [e], Jae-Kon Kim [f], Uen-Do Lee [a,b,*]

[a] Department of Green Process and System Engineering, University of Science and Technology (UST), India
[b] Thermochemical Energy System Group, Korea Institute of Industrial Technology, Republic of Korea
[c] Department of Resources and Energy Engineering, Chonbuk National University, Republic of Korea
[d] Gasification Research Center, Korea Institute of Energy Research, Republic of Korea
[e] Alternative Chemicals/Fuel Research Center, Korea Research Institute of Chemical Technology, Republic of Korea
[f] Alternative Fuel R&D Team, Korea Petroleum Quality & Distribution Authority (K-Petro), Republic of Korea
[g] School of Mechanical Engineering, Sungkyunkwan University, Republic of Korea

HIGHLIGHTS

- A pilot scale biomass-to-liquid (BTL) process was investigated for Fischer-Tropsch diesel production.
- 200 kW_{th} dual fluidized bed gasifier was integrated with 1 bbl/day F-T synthesis reactor.
- Purified syngas satisfies minimum requirements of F-T synthesis.
- F-T diesel produced successfully (1 L/h) and satisfies the automotive fuel standard.
- Fully integrated BTL system was operated successfully more than 500 h.

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ABSTRACT

Fischer–Tropsch (F-T) diesel produced from biomass through gasification is a promising alternative fuel. In this study, a biomass-to-liquid (BTL) system involving a dual fluidized bed gasifier (DFBG), a methanol absorption tower, and an F-T synthesis process was investigated for producing clean biodiesel as an automotive fuel. A DFBG, which is an efficient indirect gasifier, can produce syngas with high caloric value while minimizing the amount of nitrogen in the product gas. In order to meet the strict requirements of syngas for F-T synthesis, any contaminants in the syngas must be minimized and its composition must be carefully controlled. In this work, the syngas mainly comprised 35 vol% of H_2 and 21.3 vol% of CO. The concentrations of H_2S and COS in the syngas were less than 1 ppmV owing to the use of chilled methanol cleaning process. Furthermore, long-term operation of a fully integrated BTL system was successfully conducted for over 500 h. The results showed that the BTL diesel can be used as an alternative automotive diesel fuel.

1. Introduction

Renewable fuels from various biomass sources, the most abundant resources on the Earth, can be used to supplement the current fuel systems and address the resulting environmental issues [1]. An attractive way of using biomass is its thermochemical conversion to a conventional fuel; using this process, many types of synthetic fuels can be produced from biomass, such as hydrogen, substitute natural gas, dimethyl ether, and Fischer-Tropsch (F-T) diesel [2]. Among the thermochemical conversion processes, gasification can convert organic or carbonaceous materials into useful syngas composed of hydrogen, carbon monoxide, carbon dioxide, and methane. The syngas from biomass can be used directly as fuels or as raw materials for producing higher-value-added products through a subsequent synthesis process [3].

* Corresponding author.
E-mail addresses: 02yd@kitech.re.kr (Y.-D. Kim), ycw@kitech.re.kr (C.-W. Yang), dery01@kitech.re.kr (B.-J. Kim), mjh5635@kitech.re.kr (J.-H. Moon), freeze@kitech.re.kr (J.-Y. Jeong), pysoo80@kitech.re.kr (S.-H. Jeong), donald@jbnu.ac.kr (S.-H. Lee), jaeho@kier.re.kr (J.-H. Kim), mwseo82@kier.re.kr (M.-W. Seo), sangbl@krict.re.kr (S.-B. Lee), jkkim@kpetro.or.kr (J.-K. Kim), uendol@kitech.re.kr (U.-D. Lee).

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Nomenclature

Abbreviation

BFB	bubbling fluidized bed
BTL	biomass to liquid
CFB	circulating fluidized bed
CGE	cold gas efficiency
CTL	coal to liquid
d.a.f	dry ash free
DFBG	dual fluidized bed gasifier
FFB	fast fluidized bed
F-T	fischer-tropsch
GC	gas chromatography
GTL	gas to liquid
ID	induced draft
LHV	lower heating value
MeOH	methanol, (CH_3OH)
NDIR	non dispersive infra-red
PFPD	pulsed flame photometric detector
ppbV	parts per billion by volume
ppmV	parts per million by volume
TCD	thermal conductivity detector
TPD	ton per day

Greek symbols

γ	steam to biomass ratio
λ	excess air ratio

As a representative liquid fuel production method, the F-T synthesis process can be used to produce polymeric hydrocarbons like gasoline and diesel from a gaseous mixture of CO and H_2 through sequential hydrogenation of CO [4–7]. Since F-T diesel has enormous potential to replace crude-oil-based transport fuels, many studies have investigated its production globally since its first introduction in 1935 [8–19]. The F-T process was first applied to coal-to-liquid (CTL) processes [20]. Sasol Chevron, Conoco Philips, and Total have developed both CTL and gas-to-liquid (GTL) technologies, and the Bintulu plant has been producing F-T fuels commercially since 2007. In the case of CTL, the overall characteristics of the synthetic fuel were examined and it was found that CTL diesel has a higher cetane number and lower density than standard diesel [21].

In the biomass-to-liquid (BTL) process, the final product from biomass is a liquid. Generally, there are two types of BTL methods: direct liquefaction and indirect synthesis [22]. The latter process normally involves the integration of three processes: gasification, syngas treatment, and F-T synthesis. Appropriate selections of gasification and syngas treatment methods—as upstream processes of F-T synthesis—are important to meet the requirements of the F-T reaction [14]. In general, the H_2/CO ratio and amount of contaminants in the syngas are the most important parameters for the product yield and durability of a specific F-T catalyst [15,16]. The most widely used catalysts in F-T synthesis are Fe, Co, and Ru. The Fe catalyst is more economic than the other two catalysts [17,18], and it can be used both for low-temperature (180–250 °C) and high-temperature (300–350 °C) conversions, depending on the reactor type. Generally, the H_2/CO ratio of iron catalysts should be under 1. In contrast, cobalt needs the H_2/CO ratio between 1 and 2. A fluidized bed reactor is advantageous for biomass gasification because of excellent gas-solid contact and high thermal conductivity of solid fuels [23]; an indirect steam gasification process with a dual fluidized bed gasifier (DFBG) is the best option for BTL in terms of syngas quality [24,25]. The advantages of a DFBG have been described elsewhere [26–28]. In addition, DFB technology with biomass gasification has been well summarized by Kristina et al. [29].

Some previous studies have investigated BTL systems [30–33]. A bench-scale hydrocarbon liquid fuel production experiment was conducted by Hanaoka et al. [34]. They used a downdraft fixed-bed gasifier with oxygen-enriched air as a gasifying agent. Through F-T synthesis, 7.8 L of hydrocarbon liquid was produced, but fuel information was not provided. CUTEC developed a pilot-scale integrated BTL system. A circulating fluidized bed (CFB) gasifier and a fixed-bed F-T reactor were used for producing 150 mL/d F-T diesel. The gasifier was operated for nearly 2500 h and the F-T process was tested for nearly 900 h. Velocys adopted a microchannel reactor for the F-T synthesis process. Compared to the previous F-T reactor, the microchannel reactor enhances both heat and mass transfer rates, leading to increased F-T diesel production [35]. MicroEnergy tested a 2.5 TPD BTL unit at Naka, Japan. They developed a two-stage rotating gasifier with electrical heating, and 450 L/d of liquid fuel was produced by the system along with the generation of 125 kW of electricity. Mizushima et al. conducted a real vehicle test using the BTL fuel from MicroEnergy [36]. CHOREN in Germany was a pioneer in the commercialization of BTL technology. They developed a three-step Carbo-V gasification process based on an entrained flow reactor. In the demonstration plant, 5 ton of low-grade wood was used to obtain 1 ton of biodiesel. Their Beta plant in Freiberg, Germany, had one of the largest BTL systems in the world. However, very limited information was released to the public, even though they operated the largest demonstration plant [13].

Table 1 summarizes the development status of synthetic liquid fuel production through BTL processes worldwide. As technology providers, CHOREN, CUTEC, TRI, TUV, and Velocys have developed integrated BTL systems. Stora Enso also tested a fully integrated demonstration plant for a BTL process. Even though their demonstration plants showed successful results, they decided not to proceed with their plans to build a scale-up plant because of cost issues. Air Liquide & CEA, KIT, Fulcrum Bioenergy Inc., and British Airways have on-going projects to develop BTL processes [34–42]. However, as an emerging technology, limited information is available on the BTL projects. Moreover, it is difficult to find the details of the fully integrated system of gasification, gas cleaning, and F-T process, since most commercial approaches are confidential and multiple interactions between integrated processing steps increase the operation difficulty [43].

In this work, as a follow-up study of a long-term integrated operation of a bench-scale BTL system [32], a pilot-scale BTL process was developed for an integrated operation. The facility consists of a 200 kW_{th} DFBG; a first syngas-cleaning island for removing dust, tar, and moisture; a syngas compressing unit for the subsequent pressurizing process; a second syngas-cleaning island for removing acidic gas with chilled methanol; and an F-T synthesis process with an Fe catalyst in a fixed-bed reactor. A long-term integrated operation of more than 500 h was conducted in several attempts, and the technical feasibility of each part of the integrated system was investigated. In addition, details of the fully integrated system from biomass gasification to F-T synthesis are presented, including some trial-and-error experiments for optimization. Furthermore, representative properties of BTL diesel based on conventional fuel standards are provided. The details of the fully integrated BTL facility and results of the long-term operation in the pilot-scale plant will be useful for the understanding and further optimization of the technology as well as the development of a commercial-scale BTL process.