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Production of producer gas from waste cooking oil in a fluidized bed reactor: Influence of low-temperature oxidation of fuel

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ABSTRACT

In this study, fresh soybean oil (FSO) and waste soybean oil (WSO) were gasified with air in a bench-scale fluidized bed reactor equipped with a tar removal system. The objective of this work was to study the effect of the Equivalence Ratio (ER) on gas composition for producing producer gas and tar content. Furthermore, the gas compositions from the gasification of FSO and WSO were compared in order to study the effect of fuel compositional differences caused by low-temperature oxidation of the oil during the cooking process. As a result, it was found that low-temperature oxidation significantly changes the fuel composition which lead to WSO becomes more favorable for gasification reaction producing higher hydrogen and carbon monoxide yield. In addition, with the activated carbon filtration, the producer gas from WSO satisfied the tar requirement (<0.1 g/Nm^3) for a syngas power generation engine.

1. Introduction

The effective utilization of renewable fuels is essential for reducing local dependence on fossil fuels and mitigating greenhouse gas problems, especially considering the current needs of the related energy market [1]. Among the variety of renewable fuel sources available, there has been an increased interest in low-grade oils. These low-grade oils can replace conventional fossil fuels if their characteristics are similar to those of fossil fuels. For example, according to a report from EPRI, the Hawaiian Electric Company successfully conducted, at the Kahe Power Plant, a 0–100% co-firing test using crude Malaysian palm oil [2]. A full demonstration was also conducted using 100% bio fuel oil in a 75 MWe oil-fired power plant in Korea. A study on establishing a draft standard, based on heavy-oil standards, for the use of bio-oil in power generation is currently underway [3]. Bio heavy-oils, which are mainly composed of triglycerides, can be obtained from vegetable- or animal-derived fats and oils, and can be used in a boiler without major equipment retrofit. Apart from bio heavy-oils, a number of oils, such as biomass pyrolysis oil, black liquor from paper mills, waste glycerol, waste cooking oils, and waste lubrication oils, broadly categorized as low-grade bio-oils, are unsuitable for producing electricity in commercial power plants with their original forms. These oils have a low heating value and contain solid contaminants and acidic compounds, which lead to complications such as supply difficulties caused by ash content and viscosity, corrosion due to acid components, and clogging of pipes due to impurities. These complications make their direct utilization in commercial energy systems, such as boilers or engines, problematic [4]. These drawbacks can be addressed by the introduction of a preprocessing step such as impurity removal, neutralization of acids, and reduction of viscosity using additives. One promising solution is a system integrating a thermochemical conversion process, such as gasification with a fluidized bed system, since supply difficulties, corrosion, and clogging are not observed with gaseous fuels.

As a low-grade-oil gasifier, a fluidized bed reactor offers several advantages because it is unaffected by solid impurities in the oil and facilitates stable reactions with a wide range of fuels. In addition, the system configuration is simple even on a small scale, and a catalyst can be used during gasification.

Abbreviations: WSO, waste soybean oil; FSO, fresh soybean oil; ER, Equivalence Ratio; TG, thermogravimetry; DTG, differential thermogravimetry; TGA, thermogravimetric analyzer; LHV, lower heating value; TCD, thermal conductivity detector; FID, flame ionization detector; GC–MS, gas chromatography–mass spectrometry; CGE, cold gas efficiency.

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Small- or medium-scale distributed power generation systems, based on a bio-oil gasification-integrated energy system, that use a syngas engine or fuel cell can be introduced in rural areas that do not have a power grid or infrastructure for using fossil fuels. Locally generated low-grade oils can be used as fuels for such power plants. For example, palm mills in many areas of Indonesia that have a relatively low rate of electrification produce abundant low-grade solid and liquid byproducts [5]. If a bio-oil/biomass gasification-integrated energy system is set up for distributed power generation in the local villages of such areas, these palm oil mills could serve as renewable fuel sources for these remote places.

Around 270,000 tons of waste cooking oil is generated every year in Korea alone [6]. This waste cooking oil is treated with methanol to produce bio-diesel, which is then mixed with petro-diesel in a specific ratio and sold as commercial diesel. In Korea, over the past 10 years, the percentage of bio-diesel in commercial diesel has increased from 0.5% to 2% [6,7]. Thus, research toward the development of more efficient processes for the use of waste cooking oil as an energy source is required. Recent research has mainly focused on the production of hydrogen by reforming bio-oil and other oils using catalytic/non-catalytic gasification [8–19]. Pinto et al. carried out the gasification of coal mixed with edible oil waste (EDW) in a fluidized bed reactor and reported that coal mixed with up to 10 wt% of EDW was successfully gasified [20]. So far, there have been no studies on the air gasification of waste cooking oil.

In this study, waste cooking oil was gasified in a bench-scale gasifier equipped with a fluidized bed reactor. Soybean waste cooking oil was used as gasifying fuel. The main objective of this study was to determine the optimum reaction conditions for the production of clean producer gas for power generation. Therefore, the variation in the tar content of the producer gas obtained for different Equivalence Ratios (ER) and the influence of low-temperature oxidation of the cooking oil on the gas composition were also studied. Finally, a long-term experiment was carried out using the determined optimum reaction conditions to confirm the stability of the gasification process.

2. Experimental design

2.1. Fuels

Studies were carried out on two soybean oils: fresh soybean oil (FSO) and waste soybean oil (WSO). The FSO and WSO samples were provided by local fried-chicken restaurants. The WSO sample had been thermally treated at 170–180 °C in air. Prior to the gasification experiment, the WSO sample was filtered using a 150 μm sieve to remove any chicken residue.

The main characteristics of the fuels are shown in Table 1. Proximate analysis revealed that FSO and WSO were composed of 99.6 wt% and 99.5 wt% volatile matter, respectively. Ultimate analysis results showed that both FSO and WSO were composed mainly of carbon and hydrogen. The oxygen contents, which were analyzed separately, were 7.5 and 12.3 wt% for the FSO and WSO, respectively. Nitrogen, originating from the protein content, was also detected in both fuels. Interestingly, chlorine (0.004 wt%) was only found in WSO, which could be because of the salt used in seasoning. The higher heating values of both FSO and WSO, measured by a bomb calorimeter (Model 6400, Parr), were about 40 MJ/kg. Metal analysis showed a very low concentration of heavy metals (Cr, Cd, and Pb) in both fuels. The sodium content of WSO (27.48 ppm) was higher than that of FSO (8.74 ppm), and could be related to the chlorine content of the former. Because of the presence of carboxylic acid, both fuels showed an acidic pH of 4.3.

2.2. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. The gasification experiments were carried out in a bench-scale gasifier consisting of an oil feeding system, a fluidized bed reactor, a cyclone, and a gas quenching system.

The fuel was directly introduced into the middle of the fluidized bed reactor which located 700 mm from distributor as a continuous flow using a micro pump system (ISMATEC REGLO-Z) with a variable feed rate of 4.25–6.13 mL/min. The fluidized bed material used in the experiments was quartz sand with a mean diameter of 250 μm. The fluidized bed reactor, which consisted of a 316 SS tube with an inner diameter of 100 mm and a height of 1600 mm, was indirectly heated using an electrical heater (7 kW). In each experiment, 8 thermocouples are installed at 20 mm intervals, the reaction temperature was determined by averaging the values obtained from the three K-type thermocouples in the reactor. During the experiment, the temperature was recorded using the DASYLab software (ver. 10). The char produced was removed by the cyclone, which was designed to capture particles larger than 2 μm. Three water-cooled steel condensers operating at 10 °C, an impact separator, an electrostatic precipitator, and a fabric filter were used to capture the generated moisture and tar. Air was introduced into the fluidized bed reactor through a wind box that was heated to 350 °C by a heating band. The producer gas produced in the experiment was sampled, under steady-state conditions, at intervals of 5 min using Tedlar gas bags (1 L). The excess producer gas was burned using a pilot burner in a flare stack.

2.3. Reaction conditions

The reaction conditions for the gasification experiments are shown in Table 2. In each experiment, the amount of quartz sand used was 10 kg and the fuel feed rate was controlled according

Table 1
Main characteristic of fuels.

Proximate analysis (wt%)	FSO	WSO	Ultimate analysis (wt%)	FSO	WSO
Moisture	0.2	0.04	C	80.4	74.7
Volatile matter	99.6	99.96	H	10.1	11.9
Fixed carbon[a]	0.1	–	N	2	1.1
Ash	0.1	–	S	–	–
			O	7.5	12.3
			Cl	–	0.004
Metal analysis (ppm)					
B	3.7	10.5	Na	8.7	27.5
Cr	<0.1	<0.1	Fe	4.2	5.3
Zr	0.9	1	Ni	<0.1	0.04
Cd	n.d[b]	n.d	Pb	n.d	n.d

[a] By difference.
[b] Not detected.