Design and Analysis of the Empty Fruit Bunch Conversion Process for Multi-biofuels Production

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Abstract

The energy production from cleaner and renewable sources has attracked considerable attention due to sustainability reason and environmental concern. This study proposes the integrated process of pyrolysis, gasification, and hydrotreating for multi-biofuels production using an empty fruit bunch (EFB) residual as a biomass feedstock. The pyrolysis process is firstly used to decompose EFB to bio-oil and bio-char. Then, bio-char as a carbonaceous source with less amount of solid mass compared with EFB is gasified to produce synthesis gas, whereas bio-oil is upgraded via a hydrotreating process to biofuels. Non-condensable gas from pyrolysis and synthesis gas from gasification are sent to a water gas shift process for the production of hydrogen, which is used in the hydrotreating process. Modeling of the proposed process based on kinetics and thermodynamics approaches is performed using Aspen Plus simulator. The effects of key operating parameters on product distribution are predicted to find their optimal condition maximizing the yield of bio-oil and hydrogen products. The simulation results show that based on the EFB feed flow rate of 145 tph, the maximum yield of bio-oil from the pyrolysis process is 67.2% at an operating temperature of 500 °C. Hydrogen obtained from the integrated process is sufficient for upgrading bio-oil products.

Keywords: Empty fruit bunch, pyrolysis, gasification, biofuels, hydrotreating

1. Introduction

Fossil energy is presently the main power for driving the world economy. While the demand is increasing, the natural source of fossil fuels is limited. Furthermore, with increased utilization of this fuel type through combustion, greenhouse gas and micro-particles are released, causing global warming problems coupled with a public health concern. To relieve these problems, support of renewable energy usage has received much emphasis. The use of biomass as a potential renewable source is widely considered because it can be transformed into various types of biofuels and bio-chemicals.

Fast pyrolysis is among the various thermochemical processes that are widely used to convert solid biomass into high-value products. It involves a biomass decomposition process with rapid heat to a moderate temperature of 500 °C in the absence of oxygen. The main products are bio-oil, noncondensable gas (NCG) and biochar (carbonaceous residual) (Peters et al., 2017). Bio-oil consists of organic and inorganic compounds and its quality can be improved to obtain biofuel products through a hydrotreating process in which oxygenate compounds react with H_2 over Co-Mo or zeolite catalyst (Qian et al., 2015). Presently, steam reforming process is widely used for H_2 production from natural gas (Bloom et al., 2018), which is a limited energy source. Alternatively, biomass gasification can be used to generate synthesis gas, which is subsequently treated via water gas shift (WGS) process and pressure swing adsorption (PSA) for pure H_2 production. To improve the high energy consumption of the gasification, the pyrolysis and gasification integrated process was investigated technically and economically by Im-orb et al. (2015).

This study proposes the integrated process of pyrolysis with gasification and hydrotreating processes for biofuel production. Empty fruit bunch (EFB), the residue obtained from an oil palm milling process, is considered a raw material. The model of such the proposed process is developed using Aspen Plus simulator and used for process design and analysis. Effect of key operating parameters on the product distribution is investigated to find suitable conditions, maximizing bio-oil and hydrogen products.

2. Modeling of Pyrolysis, Gasification, and Hydrotreating Integrated Process

The conversion process of an empty fruit bunch (EFB) to biofuels consists of feed pretreatment, pyrolysis, gasification, WGS, PSA, combustion, and hydrotreating processes. Modeling of this integrated process was performed by using Aspen Plus simulator (version 10). Figure 1 shows the model flowsheet of the integrated process. In this study, EFB at the flowrate of 145 tph, which is based on the EFB residue from 21 palm milling plants in the southern part of Thailand, is considered a feedstock. The Redlich-Kwong-Soave cubic equation of state with Boston-Mathias alpha function (RKS-BM) which is the preferred thermodynamic model for calculating the physical properties of substances in the gas-processing, refinery and petrochemical processes, is used in this study (Rasul, 2015).

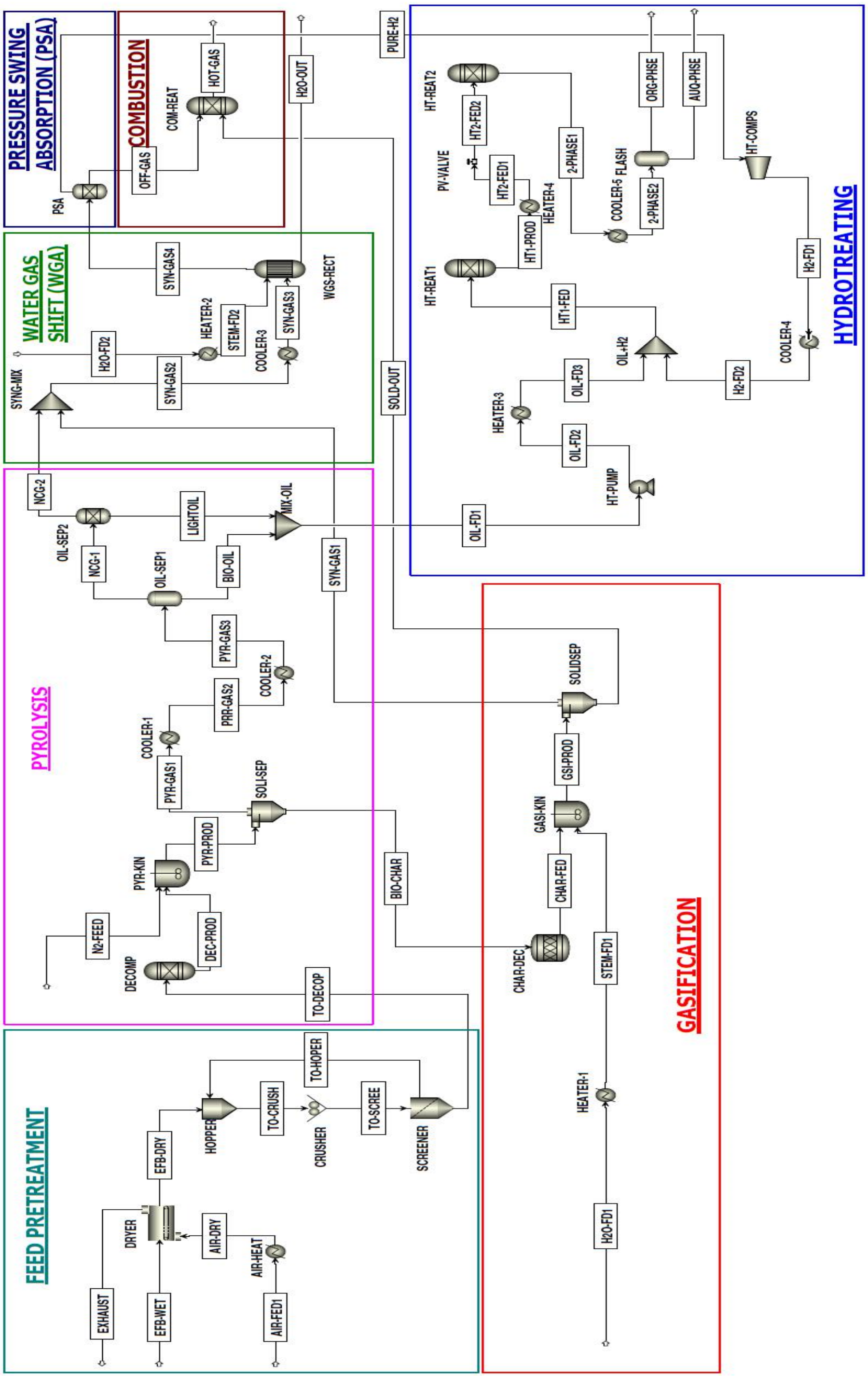

Fig.1 Flowsheet model of the integrated EFB process.

2.1. Feed Pretreatment

Fresh EFB (non-conventional component) with 7.9% moisture (an EFB-WET stream) enters the feed pretreatment section to remove water (a dryer block modeled as a contact dryer). Dry EFB is fed into HOPPER and crushed in CRUSHER for reducing its particle size to 3 mm, which is suitable for decomposing in the pyrolysis process. The SCEENER is a particle size separation; the dry EFB with the particle size higher than 3 mm is send back to the HOPPER.

2.2. Pyrolysis

Dry EFB enters the pyrolysis section in which the dry EFB is decomposed (modelled as RYield) to different biochemical components, i.e., cellulose, hemicellulose, carbon-rich lignin, oxygen-rich lignin, hydrogen-rich lignin, and water, by specifying the yield distribution according to the ultimate analysis and biochemical composition of EFB (Abdullah and Gerhauser, 2008). The decomposed products enter the pyrolysis reactor (PYR-KIN modeled by RCSTR), which is operated at 500 °C and 1 bar. The distribution of the pyrolysis products is explained by multi-step kinetic reactions of decomposition and volatilization (Rezaei et al., 2008). Nitrogen (N2-FEED) is used as a carrier gas. Pyrolysis gas obtained is separated from solid biochar in a separator (SOL-SEP) and is cooled down (COOLER-1 and COOLER-2). Non-condensable gas (NCG) is removed from the bio-oil using separators (OIL-SEP1 and OIL-SEP2). Bio-oil is then sent to the hydrotreating process.

2.3. Gasification

Biochar as a by-product of the pyrolysis process is used as a gasification feedstock for synthesis gas production. It is first decomposed into element composition (CHAR-DEC modeled by RStoic) before entering to the gasification reaction section modeled by RCSTR (GASI-KIN reactor) with steam. The kinetics of the steam-carbon, boudouard, methanation, water gas shift, and methane-reforming reactions are considered for biochar conversion (Eikeland and Thapa, 2017). The synthesis gas product is separated from biochar residuals in the SOLIDSEP separator and then sent to the WGS process to increase H_2 yield and fraction.

2.4. Water Gas Shift Process

Synthesis gas from the gasification is mixed with NCG from the pyrolysis process (SYNG-MIX) and cooled down before it is fed to WGS reactor (WGS-RECT) which is modeled by the REquil rector model. In the WGS reactor, CO reacts with steam for H_2 production and CO_2 is found as by-product from this process. The effect of operating temperature and S/C ratio on the WGS reactor is analyzed under the working pressure of 48 bar (Ranzi et al., 2008).

2.5. Pressure Swing Adsorption

H_2 in synthesis gas stream (SYN-GAS4) is purified in the PSA unit using a separator model (Sep2). Adsorbent gas (OFF-GAS stream) is used as a heat source in the process and 99.99% H_2 stream is fed into the hydrotreating process for bio-oil upgrading.

2.6. Combustion

The solid residual from the gasification process is sent to the combustor (COM-REAT, modeled by RGibb) to burn with offgas from PSA unit at 1090 °C and 2 bar (Rezaei and Mehrpooya, 2018). The heat generated from this process can be utilized for heat and power generation in the process.

2.7. Hydrotreating

Bio-oil from the pyrolysis process goes through the pump (HT-PUMP) and heater (HEATER-3) to increase pressure and temperature while H_2 from the PSA unit is compressed and cooled down (HT-COMPS and COOLER-4). Both reactants are mixed (OIL+H2 mixer) and fed into the stabilization reactor (HT-REAT1). The treated oil is then sent to the deoxygenate reactor. These two reactors are simulated using RYield reactor model under the operating conditions of 270 °C and 170 bar, and 350°C and 170 bar, respectively. The hydrocarbon product yield distribution is based on the bio-oil upgrading from experimental data (Peters et al., 2015).

3. Results and Discussion

3.1. Model Validation

The model of the pyrolysis process as the major unit in the EFB conversion process is validated with the experimental results of the EFB pyrolysis in a fluidized bed reactor (Abdullah and Gerhauser, 2008). Under the operating temperature and pressure of 500 °C and 1 bar, the pyrolysis products consist of 67.23% bio-oil, 20.05% NCG, and 12.71% biochar. The predicted yield of biofuels (59%) is in good agreement with the experimentals with a relative percent error of 3.4% based on biofuel production.

Table 1 Comparison of the predicted and experimental results for the EFB pyrolysis.

Product distribution (%)	Simulation	Experimental	Relative error (%)
Bio-oil	67.23	65.21	3.10
NCG	20.05	23.43	14.43
Biochar	12.71	11.36	11.88

3.2. Effect of Key Operating Parameters

Figures 2(a)-(c) show the effect of gasifying temperature, steam flow rate and residence time on the composition of the synthesis gas product. The maximum concentration of H_2 in the synthesis gas can be obtained at 900 °C, 240 tph steam feed and 1.7 sec for residence time condition. The effect of the S/C ratio and operating temperature for WGS reactor on the H_2 concentration in synthesis gas is shown in Figures 2(d) and (e). The maximum fraction of H_2 product is obtained at the S/C ratio of 0.3 and 240 °C. In addition, the amount of H_2 is increased by 31.2% from that obtained from the gasification process. Considering the PSA process, the high purification of H_2 (99.99%) with the flow rate of 6194 kg h^{-1} is achieved and the heating value of syngas (LHV) from the combustion process is 1,992.3 MJ kg^{-1}. After hydrotreating, the yield of bio-oil is 59% consisting of C_5-C_{18}.

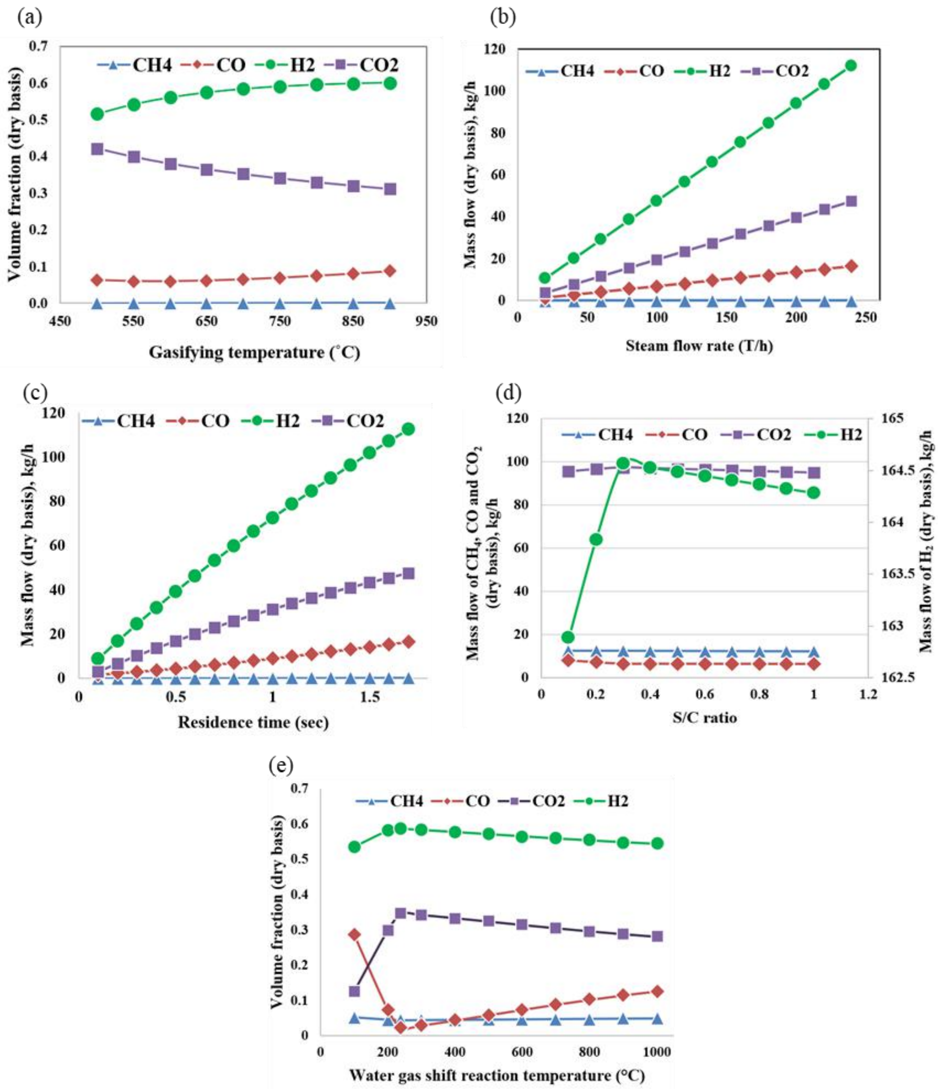

Fig. 2 Effects of operating parameters on production distribution: (a) gasifying temperature, (b) steam flow rate (tph), (c) residence time (s), (d) S/C ratio in WGS process, and (e) WGS temperature.

4. Conclusions

In this study, the pyrolysis process of empty fruit bunch (EFB) integrated with gasification and hydrotreating processes was designed and analyzed for biofuels production. The yield of bio-oil obtained from the pyrolysis process was 67.23% at 500 °C and 1 bar. Regarding the gasification process operated at 900 °C and 1 bar, the maximum yield of H_2 was 4722 kg h^{-1} when the steam flow rate of 240 tph was employed. The H_2 concentration WGS process run at the S/C ratio of 0.3 was increased by 31.2%. Regarding the hydrotreating process, the 6194 kg h^{-1} of H_2 was required for bio-oil upgrading and 59% yield of liquid biofuels fraction was achieved.

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