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Techno-economic Assessment of FT Unit for Synthetic Diesel Production in Existing Stand-Alone Biomass Gasification Plant Using Process Simulation Tool

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For alternative thermo-chemical conversion process route via gasification, biomass can be gasified to produce syngas (mainly CO and H_2). On more applications of utilization, syngas can be used to synthesize fuels through the catalytic process option for producing synthetic liquid fuels such as Fischer-Tropsch (FT) diesel. The embedding of the FT plant into the stand-alone based on power mode plants for production of a synthetic fuel is a promising practice, which requires an extensive adaptation of conventional techniques to the special chemical needs found in a gasified biomass. Because there are currently no plans to engage the FT process in Thailand, the authors have targeted that this work focus on improving the FT configurations in existing biomass gasification facilities (10 MW_{th}). A process simulation model for calculating extended unit operations in a demonstrative context is designed by commercial software. The aim of this work is to develop detailed process flow diagram for the FT technology in order to subsequently study the economic feasibility based on once-through mode. A cost analysis is performed to find out the convenience of the proposed solutions.

1. Introduction

Large amount usages of fossil fuels have led the government of Thailand to develop an energy plan which is aiming to increase 20 % of its fractional renewable fuels by 2020 for short term. To achieve this target, Thai's policy has promoted the usage of crop and agricultural sources in the second generation, launching the Small Renewable Energy Power Plant Program in 2008 (EPPO, 2013). Biomass gasification followed by the synthesis of FT diesel is one promising project of the main conversion pathways currently being developed to produce transportation fuels. Haro et al.(2013) investigated by the ASPEN PLUS process simulator due to commercial competitiveness of biochemical synthesis route for a plant size of 2,140 dry t/d of wood chip - 500 MW_{HHV}. Swanson et al.(2010) also presented a process model in Aspen Plus to estimate fuel production costs from gasified corn stover, and also compared the techno-economic benefits of different bio-refineries production processes from syngas using Aspen Plus. These results are not currently competitive. In fact to these approaches, the designing completely new infrastructure has directly

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affected to the structural production cost of synthetic fuels, which may not be improve cost-effective for the apparent competition in unit costs when compared with fossil fuel.

A new idea was carried out at a relatively high-level for the thermal and chemical conversion route, is that building the FT plant close to the syngas producer or integrated stand-alone power unit based on biomass gasification plant. In particular, modification of a new FT synthesis embedded with existing gasification infrastructures i.e., electrical power network, steam, waste water, etc can be retrofitted with additional some units rather than needing completely new infrastructure. However, it has been pointed out that the production cost may be more cost-effective to construct a dedicated unit for processing of synthetic liquid fuels, due to the apparent completion in unit costs between fossil fuels and premium fuels as GTL process. Because there are currently no plans to engage the FT process in Thailand, the authors have targeted that this work focus on improving the FT configurations in existing gasification facilities. A stand-alone power unit based on biomass gasification plant is considered, in which input 10 MW_{th} of woodchip feedstock per day is processed, separately producing 3 MW_{th} of synthetic diesel. Data used to simulate the gasification unit operations were obtained from visiting sites, while the FT configurations were provided from our pilot scale. A process simulation model for calculating extended infrastructures in an industrial context was designed by ASPEN Plus® V7.2. The aim of this work is to develop detailed process flow diagrams for the FT technology in order to continuously study the economic feasibility. A cost analysis is performed to find out the convenience of the proposed solutions. Figure 1 shows the configuration of the FT plant after the planned rebuild. Existing gasification infrastructures and introduction of new FT unit operations include: syngas cleaning and conditioning (A100), FT synthesis (A200), and power generation (A300).

2. Process description and simulation

The input for considered concept was the roughly cleaned and separated syngas, with a molar H_2/CO ratio of 1, from the gasification section. Before entering the synthesis plant, syngas was compressed in gas holders at a temperature of 308 K and with pressures of 20 bar, and then was either fed into dry or wet cleaning section to roughly eliminate some kinds of impurities. The acid gas level of the syngas is one of the most significant parameters influencing the operating performance of the FT catalyst. Therefore, A100 was additionally designed to ensure the complete removal of the organic compound and then did not effect to FT catalyst later. At the beginning, the raw syngas was scrubbed of the bulk of the hydrogen sulfide by an absorption column before being heated and sent to a shift reaction, where it was purified to less than 1 ppm H_2S to avoid poisoning the FT catalyst. Next, it is important to note that the H_2/CO ratio between the different syngas may vary depending on what synthesis process was chosen.

When large amount of cleaned syngas leaves the acid gas removal unit, the H_2/CO ratio may not be suitable for subsequent FT synthesis step which the required H_2/CO ratio was to be 2 (Trippe et al., 2011; Trippe et al., 2013). This point can be achieved by letting part of the syngas bypass the shift step corresponding to water gas shift (WGS) reactor. The resulting gas was a mixture of hydrogen and carbon dioxide, where CO_2 can be separated by physical absorption. A portion of the H_2-rich stream from the purified unit was sent to the FT synthesis in order to provide precisely the stoichiometric amount of H_2 to react with the CO in the FT reactor. Lower pressure (<10 bar) case under reaction temperature at 453 K represented an alternative in the current technological development of the FT catalyst in the pilot plant in KMUTNB and were therefore proposed in this study. For FT synthesis (A200), cleaned syngas was catalytically reacted and condensed to produce raw mixtures of hydrocarbons via the FT reaction. Fractionation column, where raw fuels were further refined into naphtha and diesel fractions. This diesel fraction was given the final diesel product which was ready for use without further treatment. Unconverted syngas and light gaseous hydrocarbons (Off-gas) from the fractional column were combusted in an external-fire gas turbine to provide electric power (A300).

The process flowsheets in this work were simulated by ASPEN Plus® program under the academic license, as moreover, the lack of a library identified model was compensated by using FORTRAN codes nested within the ASPEN Plus® input file. The design and simulation of the gasification step, including the raw syngas composition, were modelled using a correlation relationship based on data from our testing facilities. For FT reactor, a kinetic based model library provides RPLUG (PFR) reactor by specifying with a user subroutine as Langmuir-Hinshelwood-Hougen-Watson (LHHW) type was created.

$$-R_{CO} = \frac{k_{CO} b_{CO} P_{H_2} P_{CO}}{\left(1 + b_{CO} P_{CO}\right)} \tag{1}$$

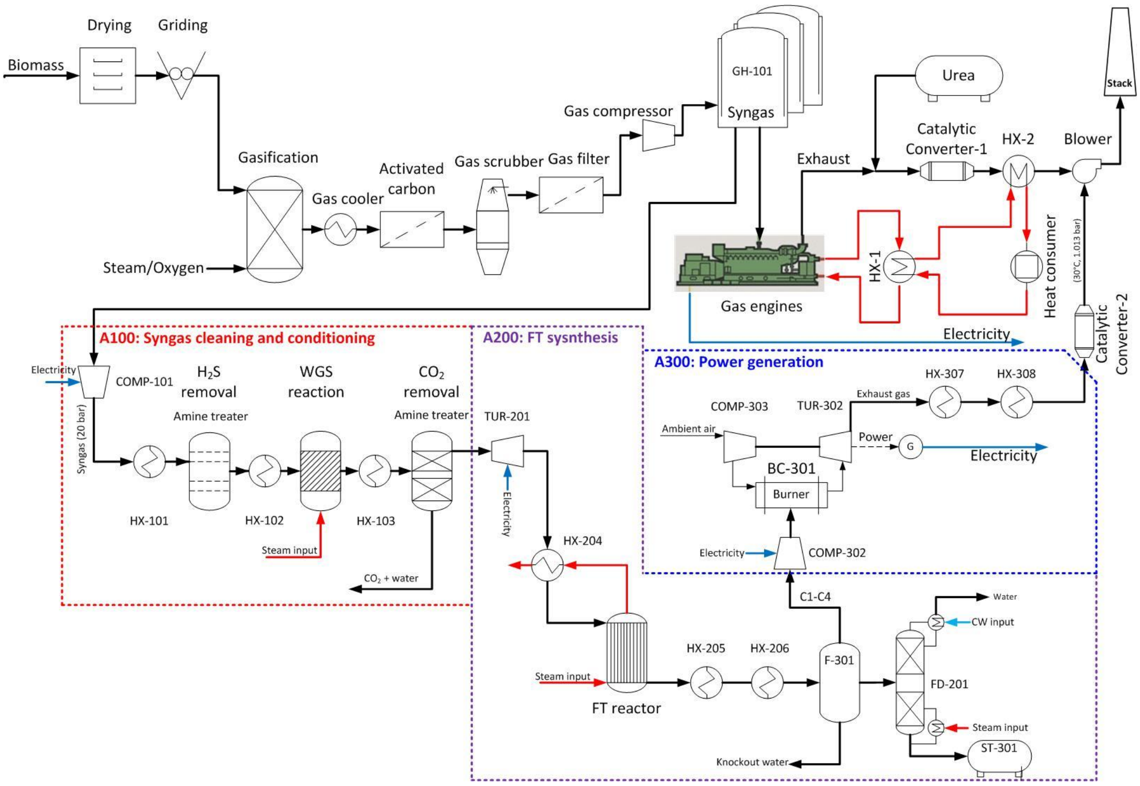

Figure 1: Process flow diagram of gasification and power generation plants in Thailand with embedded FT process (A100-A300)

A LHHW rate equation for carbon monoxide was developed by our research group (Hunpinyo et al., 2013). The kinetic rate constant, k_{CO} (0.586 mol/s•kg_{cat}•bar), and the CO adsorption constant, b_{CO} (1.867 bar^{-1}), were verified experimentally in a fixed bed reactor (FBR) operating at a wide range of temperature (433-493 K). A set of kinetic data was filled to model for the materials and energy balance calculations for FT plant. Eq.(1) allows for the calculation of catalyst weight which can then be used to size and cost the reactor. The conversion from catalyst weight to reactor volume assumes a 40 % catalyst loading by volume, which equates to 1,200 kg_{cat}/m^3. The chosen reactor temperature and pressure are 453 K and 4 bar based on the performance estimation to achieve the conversion and selectivity as well.

3. Financial analysis and assumptions

After material and energy balances had been done, the cost estimation was performed subsequently. All costs associated with the conceptual design were decomposed into a hierarchy of levels. For this study, they can be calculated from the two methods in which they were combined between study and preliminary estimate for making fixed capital investment. The applied these methods implied uncertainties of ±30 %. Costs for common equipment such as pumps, compressors, heaters and heat exchangers were calculated by the ASPEN Icarus Process Evaluator (IPE). The costs of core processing units in gasification and FT synthesis parts were separately estimated by our local information. They were calculated based on the existing pilot scale configurations and sizes fabricated in Thailand. The economy of scale was embedded in the follwing relationship, which exponential scaling was applied to adjust the purchased equipment costs using Eq(2):

$$Purchased\ cost\ of\ each\ area\ (C_{IC}) = C_O \cdot \left(\frac{S}{S_O}\right)^n \cdot \left(\frac{CEPI}{CEPCI_O}\right) \quad (2)$$

The cost of each scaling unit (S) was based on the reference scaling unit (So) and base cost (Co), which was adjusted for the time dependent equipment cost changes using the Chemical Engineering Plant Cost Index (CEPCI). The total capital investment can be estimated using ratio factors for direct and indirect capital investment according to Turton et al. (Turton et al., 2008), as presented in Eq(3).

$$Fixed\ Capital\ Investment\ (FCI) = C_{TIC} \cdot \left(1 + \sum_{i=1}^{n} f_i\right) \qquad 3.1\ (3)$$

C_{TIC} is the total cost of installed main equipment components for all the areas, f_i is the ratio factors for direct capital investments such as instrumentation and control systems, piping, electrical system, building, yard improvement and service facilities as well as the ratio factors for indirect capital investment such as engineering and supervision, construction and legal expenses, contractor's fee and contingency. Based on conventional gasification units in operation it was assumed that 95 % annual availability (7,000 h/y) is feasible for the commercial plant.

4. Results and discussion

4.1 Model results (mass and energy balances)

Considering the syngas input to the FT synthesis, Table 1 Illustrations the mass and energy balances for the diesel production from gasified biomass. In all considered processes the syngas input and output was identical in terms of mass flow and LHV (lower heating value) content. The total energy efficiency calculated according to Eq(4), where the calculated value of this process was to be 45.52 %.

$$Biomass-to-all\ products\ efficiency\ (\%) = \frac{liquid\ products\ (MW_{th}) + output\ electricity\ (MW_e) + input\ thermal\ (MW_{th})}{biomass\ (MW_{th}) + \dfrac{input\ electricity}{\eta_e = 0.35}\ (MW_{th}) + input\ thermal\ (MW_{th})} \qquad (4)$$

4.2 Economic evaluation

Total product cost without depreciation also takes into account raw material, the total operating and maintenance costs, utilities consumption rates, and the total fixed charges etc., in which the FT plant operates. Further economic assumptions used for the economic assessment were tabulated in Table 2. To account for price developments of equipment and financial components, the investment data were converted from US dollar (USD) to Thai Baht (THB), using the yearly average exchange rate of the respective year, and updated to the year 2013. The exchange rates were taken from the Thailand commission at 30 THB/USD (www.freecurrencyrates.com).

4.3 Discussion and sensitivity analysis

The production cost sensitivity to changes in input variables for key financial performance parameters was assessed using the tornado diagram, with sensitivity represented by the blue bars in the lower level of Figure 2. The results presented for 3 MW_{th} of syngas input indicates a product cost of \$ 1.768/LDE (litre-diesel-equivalent). Firstly, the catalyst cost for FT reactor considered as the low sensitivity parameter which affects FT liquid production cost less than ±\$ 0.03 per litre. Secondly, a reduction in plant performance of 6,000 h/y increased the product cost \$ 1.913/LDE, while a rising of the capacity factor from 80 % up to 91 % (8,000 h/y) decreased the product cost \$ 1.66/LDE.
Thirdly, a reduction of the purchased electricity of approximately 15 % (from 0.064 \$/kWh down to 0.054 \$/kWh) implied a decrease of the production cost of approximately 5 %. Fourthly, a decrease of 20 % of the FCI resulted in an important reduction of the FT liquid product cost of more than 9 % (from 1.96 x10^6 US\$ down to 1.568x10^6 US\$) with a production cost lower than 1.595 US\$/L. Lastly, syngas feedstock cost is a significant portion of the product value and therefore a highly sensitive parameter. The syngas feedstock cost was varied between 0.078 and 0.146 US\$/Nm^3 due to more expenditures of the upstreams (varied biomass price and energy consumption during gasification operations), FT liquid production cost was affected by a range of approximately 1.58 and 2.023 US\$/LDE.

5. Conclusions

In this study, a conceptual techno-economic analysis of the production of synthetic biofuel integrating FT synthesis with the existing gasification plant (10 MW_{th} of biomass input in Thailand) was modeled and presented for 3 MW of syngas input. The performance of FT synthesis in term of yield of liquid fuels was performed with respect to the kinetic expressions in the feed syngas under once-through mode with electricity and heat co-productions. The overall energy efficiency of biomass-derived syngas to liquid fuel was 45.51 %. Moreover, the sensitivity analysis states that the FT liquid production costs are highly influenced by the uncertainties of fixed capital investment (FCI) and syngas feedstock price. These parameters have emphasized to the importance of economies of scale for the competitiveness of synthetic liquid fuels.

Table 1: Mass and energy balances for feeding syngas inlet throughout FT process

Syngas capacity	Stand-alone biomass (10 MW)	Case study CHP (5.04 MW)	FT (3 MW)
Input to system boundary	MW	MW	MW
- Electricity supplied to CHP	0.252	0.231	-
- Thermal supplied to FT	-	-	1.897
- Electricity supplied to FT	-	-	0.436
Output from system boundary	MW	MW	MW
- Electricity production from CHP	2.81	1.76	-
- Thermal production from CHP	3.72	2.34	-
- Electricity production from FT	-	-	0.445
- Thermal production from FT	-	-	0.594
- Liquid production from FT	-	-	1.142
Energy efficiency (LHV basis)	%	%	%
- From syngas to electricity	33.77	30.87	7.25
- From syngas to thermal	42.51	41.05	9.67
- From syngas to liquid	-	-	18.59
- Total syngas to all products	76.28	71.92	35.52
Energy efficiency (LHV basis)	%	%	
- From biomass to electricity	27.31	15.98	
- From biomass to thermal	34.74	21.26	
- From biomass to liquid	-	8.28	
- Total biomass to all products	62.05	45.52	

Table 2: Summary of economic assumptions

Parameters	Values
Constant dollar value	2013
Minimum acceptable rate of return, m_{ar}	0.10/y
Debt/Equity	60 % / 40 %
Plant lifetime	20 y
Construction period	2 y
- 1st year	75 %
- 2nd year	25 %
Construction inflation rate, fraction/y	0.028
Start-up time	24 months
Corporate income taxation (case in Thailand)	23 %
Salvage value	Neglected
Plant capacity factor (7,000 h/y)	80 % annual availability

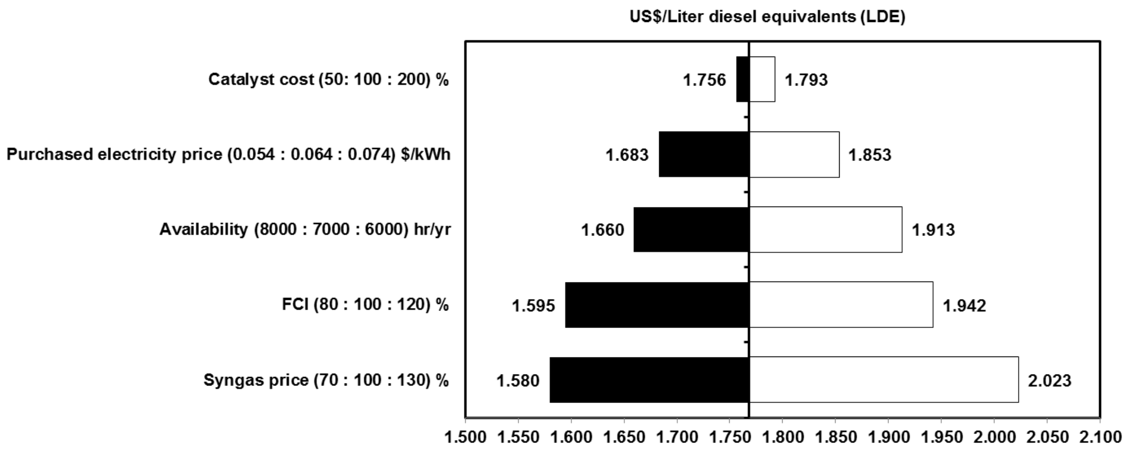

Figure 2: Tornado diagram of FT liquid fuels cost sensitivity to changes in input values (base line values shown in y-axis)

References

Energy Policy and Planning Office (EPPO), 2013, Thailand’s renewables energy policy <www.eppo.go.th> accessed 24.11.2013

Free currency exchange rates, 2013, USD to THB <www.freecurrencyrates.com> accessed 15.12.2013

Haro P., Ollero, P., Trippe, F. 2013. Technoeconomic assessment of potential processes for bio-ethylene production. Fuel Processing Technology, 114(0), 35-48.

Hunpinyo, P., Narataruksa, P., Tungkamani, S., Pana-Suppamassadu, K., Chollacoop, N., Sukkathanyawat, H., Jiamrittiwong, P. 2013. A comprehensive small and pilot fixed bed reactor approach for testing Fischer-Tropsch catalyst activity and performance on BTL route. Arabian Journal of Chemistry,DOI: 10.1016/j.arabjc.2013.11.004

Swanson, R.M., Platon, A., Satrio, J.A., Brown, R.C. 2010. Techno-economic analysis of biomass-to-liquids production based on gasification. Fuel, 89, Supplement 1(0), S11-S19.

Trippe, F., Fröhling, M., Schultmann, F., Stahl, R., Henrich, E. 2011. Techno-economic assessment of gasification as a process step within biomass-to-liquid (BtL) fuel and chemicals production. Fuel Processing Technology, 92(11), 2169-2184.

Trippe, F., Fröhling, M., Schultmann, F., Stahl, R., Henrich, E., Dalai, A. 2013. Comprehensive techno-economic assessment of dimethyl ether (DME) synthesis and Fischer–Tropsch synthesis as alternative process steps within biomass-to-liquid production. Fuel Processing Technology, 106(0), 577-586.

Turton, R., Bailie, R.C., Whiting, W.B., Shaeiwitz, J.A. 2008. Analysis, Synthesis and Design of Chemical Processes. Pearson Education.