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Biomass to methanol plant based on gasification of palm empty fruit bunch

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Abstract. Biomass from Empty Fruit Bunch (EFB) has the potential to be employed as raw material for renewable energy sources in Indonesia. EFB can be efficiently converted into valuable fuel products through gasification to produce syngas. Syngas is a suitable basis for added value products development. One of type biomass that has big potential to be utilized is palm EFB biomass. Research about methanol synthesis from various biomass has been done, though little research about methanol production based on EFB gasification. The purpose of this research is to simulate methanol plant model based on gasification of palm EFB. The method covers the step to perform a simulation of the model and methanol plant design. Electric power requirement has been investigated at 3 417 kW, and 67 % of its demand can be fulfilled by steam generation cycle and internal combustion engine (ICE) fuelled by off-gas, while the deficit fulfilled by diesel powered ICE. The flow rate of methanol produced is 85 % of EFB feed flowrate. Energy efficiency is 92 % once electricity energy added to liquid product energy content. The developed model reflects the initial step toward circular economy principals as well as the basis for analysis of the methanol production from EFB biomass gasification profitability.
Keywords: Aspen Hysys, efficiency, renewable energy, simulation, syngas, waste to energy

1. Introduction

The limitation of the resources and their efficient use have become the main issues in strategic economic development in Europe and over the world [1]. Taking into account the rate of the resources' exploitation and their associated environmental impact, the valorisation of the biomass gasification technology allows the society to use the biowaste as raw material for growing energy and materials needs. Besides this, such technology leads to economic profitability as well as to diminutions of land use for biowaste accumulation and climate change [2].

Biomass to be used as one of energy source can be done through the gasification process. Gasification is a thermochemical process that converts biomass into a gas called a producer gas or synthetic gas (syngas) using a little air or oxygen/steam. Syngas is a fuel-based mixture consisting mainly of hydrogen (H_2), carbon monoxide (CO), and methane (CH_4) [3]. According to the reference [4], gasification reactions involve several series of chemical reactions such as drying, pyrolysis, combustion processes, gasification processes, and auxiliary processes such as gas and water phase displacement reactions.

Syngas is a raw material for most other chemical products, such as methanol, ammonia, and Dimethyl Ether (DME). One of the kinds of biomass that has big potential to be utilized is palm empty fruit bunch (EFB). On the year 2014 in Indonesia, total EFB as generated was 17.43×10^6 t [5], and in the year 2015, it was 30.6×10^6 t [6].

Syngas can be further processed into various type of fuel and chemical, and one of them is methanol as a good example of the added value product development and beginning of the syngas valorisation. Methanol has chemical formula CH_3OH and often abbreviated MeOH. Methanol is toxic, light, colorless, volatile, and flammable liquid with a distinctive odor similar to ethanol. The lethal dosage of methanol if ingested is 100 mL, and 10 mL can cause blindness [7]. Major methanol usage is as a fuel; it can be used as gasoline blend stock, bunker fuel for ships, a reactant of bio-diesel making reaction, fuel for power generation [8], and feed of DME production thru indirect synthesis method [9].

Methanol synthesis is a complex process, and normally involve catalyst to increase the reaction rate. In methanol synthesis, either CO or CO_2 both hydrogenates to methanol. The reactions of the synthesis are [10, 11].

$$CO + 2H2 \leftrightarrow CH3OH \tag{1}$$

$$CO2 + 3H2 \leftrightarrow CH3OH + H2O \tag{2}$$

$$CO2 + H2 \leftrightarrow H2O + CO \tag{3}$$

The production of methanol is heavily influenced by thermodynamic equilibrium. It is limiting the process to a low conversion, and thus the recycling of the outlet is required if a high conversion is desired. The reaction itself is highly exothermic [11] and needs cooling to maintain the temperature at the reactor. The equilibrium constant of methanol is dependent on temperature [11].

The production of methanol from syngas may take place under low or high pressure. The high-pressure process operates typically at 25 Mpa to 35 Mpa and 320 °C to 450 °C while the low-pressure process operates at 5 Mpa to 10 Mpa and 200 °C to 300 °C [11]. The low-pressure process has been used since 1960 until present [11].

Studies on simulation of gasification process based on biomass gasification into syngas and then to methanol had been done Clausen et al. [12] where a methanol production based on gasification of woody biomass in a fluidized bed two stages gasifier has been discussed, and study by Andersson et al [13] about techno-economic analysis of methanol production in existing pulp and paper mill. Other research for methanol synthesis based on gasification were conducted by Zhang et al. [14] on simulation of methanol production based on biomass gasification in interconnected beds and study carried out by Leduc et al. [15] regarding cost modelling of the application of methanol production based on residues of palm oil biomass.

The specific study developed for palm empty fruit bunch simulation has not yet been found. Hence this study was aimed to provide a model of methanol plant based on EFB gasification and simulate methanol plant model developed by using Advanced System for Process Engineering Hysys (Aspen Hysys). In this paper, by referring to [16], the developed model was simulated to obtain the mass balance of the plant, methanol yield, energy efficiency, power generation and consumption.

2. Methodology

2.1. Modelling steps undertaken

The following steps have been undertaken to perform the modelling.

i) Collect information on existing models of methanol plant that were available.

ii) Perform the simulation by utilizing process engineering simulation tools. In this study, Aspen Hysys has been utilized.
iii) Prepare material and energy streams to find methanol yield, process efficiency, and energy recovery.

Process Flow Diagram (PFD) of methanol synthesis as well as its important parameters were developed and shown on Figure1. Methanol plant design has been elaborated and described in methanol plant design section. The technology and process configuration used for simulation purposes on the developed model were adopted research's results done by [7, 12–14].

2.2. Methanol plant design

2.2.1. Simulation tools. The simulation was done by using Aspen Hysys process simulator. Aspen Hysys has been used in several studies to simulate biomass gasification [17, 18] and DME production [19]. The various components that comprise Aspen Hysys provide an extremely powerful approach to steady state process modelling. The user describes the process in terms of pieces of equipment interconnected by process stream, and the program solves all the mass/energy/equilibrium equations, taking into consideration the specified design for the units [20]. Feedstock as EFB is not a default component in Aspen Hysys and must be put manually as Solid Hypothetical component. The input of EFB as a hypothetical solid component was based on the ultimate analysis of EFB measured. EFB Feedstock used for simulation is dry ash free (daf) base. Process Flow Diagram (PFD) of the methanol plant was shown in figure 1. Developed PFD comes with energy flow detail.

2.2.2. Biomass feedstock. The feedstock used was Empty Fruit Bunch (EFB). The composition of the EFB was based on dry ash free base (daf), and raw composition taken from [21]. Based on the ultimate analysis chemical formula can be determined [18]. In 100 g of biomass, there is 51.67 g of carbon. Mass in grams divided by carbon molecular weight (12 g mol^{-1}) will give the result of 4.306 mol of carbon. The same is applied to other elements, which lead to the following chemical formula for EFB Biomass: $C_{4.306}H_{6.176}O_{2.587}N_{0.048}S_{0.003}$ and this chemical formula is used as an input to Aspen Hysys as a hypothetical solid component. The input of EFB is at 6.16 t per h, based on [22].

2.2.3. Biomass pre-treatment. Before the gasification process, raw biomass in any form needs to go through the pre-treatment process. This pre-treatment process was consisting of several parts, such as granulator, dryer, hammer mill, and pelletizer [23]. In the form of pellets, EFB has a greater energy density, reducing the bridging problem in gasifiers that use biomass with non-uniform sizes [23]. According to [24], with pelletizing, the bulk density of EFB increases almost three times after the pellet-making process. The energy required for EFB pellet making is 210 kWh/dry long fiber [25]. It was assumed that dried EFB is the same as long dry fiber (DLF).

2.2.4. Gasification. The process of gasification occurs in Circulating Fluidized Bed (CFB) gasifier. Gasifier used Steam–Oxygen as an oxidant. Oxygen supplied by the cryogenic air separation process. The composition of the syngas as result of gasification was calculated based on equilibrium reaction at 900 °C, and the process assumed isothermal during the gasification reaction [26]. Excess heat from reactor used as heat for steam generation (steam generator I), since reactor cooled using water, and water will turn into steam. This steam was utilized further for power generation and gasification oxidant supply. Some of the steam generated flown into a steam turbine and combined with other steam generated by waste heat to produce electricity. From the CFB gasifier, syngas outlet cooled to 400 °C, before entering Water Gas Shift (WGS) reactor. Raw syngas outlet was filtered using bag house filter to remove particulates. The electricity consumption of the air separation unit was based on [27] at 1.0 MWe kg^{-1} O_2 s^{-1}

2.2.5. Water gas shift. WGS reactor intended to adjust for the molar ratio of H_2 CO^{-1} equals 2 for methanol synthesis requirement [9]. The temperature of the reaction is at 400 °C and pressure 1 000 kPa based on [18]. Before the acid gas removal process, syngas cooled to 25 °C [9]. Gibbs reactor was used to simulate the reaction and amount of steam supplied to the WGS reactor was 1 950 kg h^{-1}. Type of WGS used is high-temperature WGS because it favors WGS reaction with a greater reaction rate [18].

2.2.6. Water removal and syngas cleaning. Water removal was modelled using separator as a dryer. And acid gas was removed by rectisol process [28]. The removal process modelled by water separator that removes water content until below 1 % mol, though 1 % mol is still acceptable [18]. After water removed, syngas entering acid removal modelled as component splitter. CO_2 and H_2S assumed removed at 90 % and 100 % [18].

2.2.7. Methanol synthesis. Sweet syngas is compressed into 5 000 kPa (5 MPa), according to the operating pressure stated on [16]. The reactor used is Gibbs reactor to simulate the synthesis of Methanol and reactions involved is equilibrium reaction based on [15]. The operating temperature of the reactor was based on [16] at 200 °C. The temperature maintained at 200 °C throughout the reaction. Water jacketed cooler is used to maintain temperature of methanol reactor, and water as a cooler will turn into saturated steam by absorbing heat of Methanol synthesis reaction. Steam produced was a part of steam integration at steam generator II. Product of Methanol reactor was cooled to 60 °C, then separated by Gas – Liquid separator where unconverted syngas recycled back to Methanol synthesis reactor. On this simulation, 79 % of unconverted is recycled, and 21 % is sent to off-gas line and further used as fuel of gas engine for electricity generation [9]. Liquid outlet of Gas-Liquid separator flows to purification section.

2.2.8. Distillation. The distillation process only occurred in one distillation tower. It was mainly to separate CO_2 and other light gasses with Methanol and water. The tower has five stages and feed stage located on stage number 1 from condenser at the top. The gas as a top product mixed with the outlet gas from Gas – Liquid separator and sent as a fuel genset. Bottom product contains methanol, and small amount of water. Methanol recovered was > 98 % purity and this is satisfied methanol specification based on [29].

2.2.9. Steam and power generation. Steam generation for the process and power generation were from the plant's excess heat. There were two steam generators available. The first. was steam generated by excess heat from CFB gasifier and was named as steam generator I as shown on figure 1. The second was combination waste heat from WGS reactor, Methanol reactor, and E-100, all were combined as steam generator II as shown on figure 1. Power for methanol plant was generated by using one steam turbine at steam generator I and II system, and two genset that were driven by Internal Combustion Engine (ICE) that was fueled by off-gas, and another genset driven by ICE, fueled by another type of fuel.

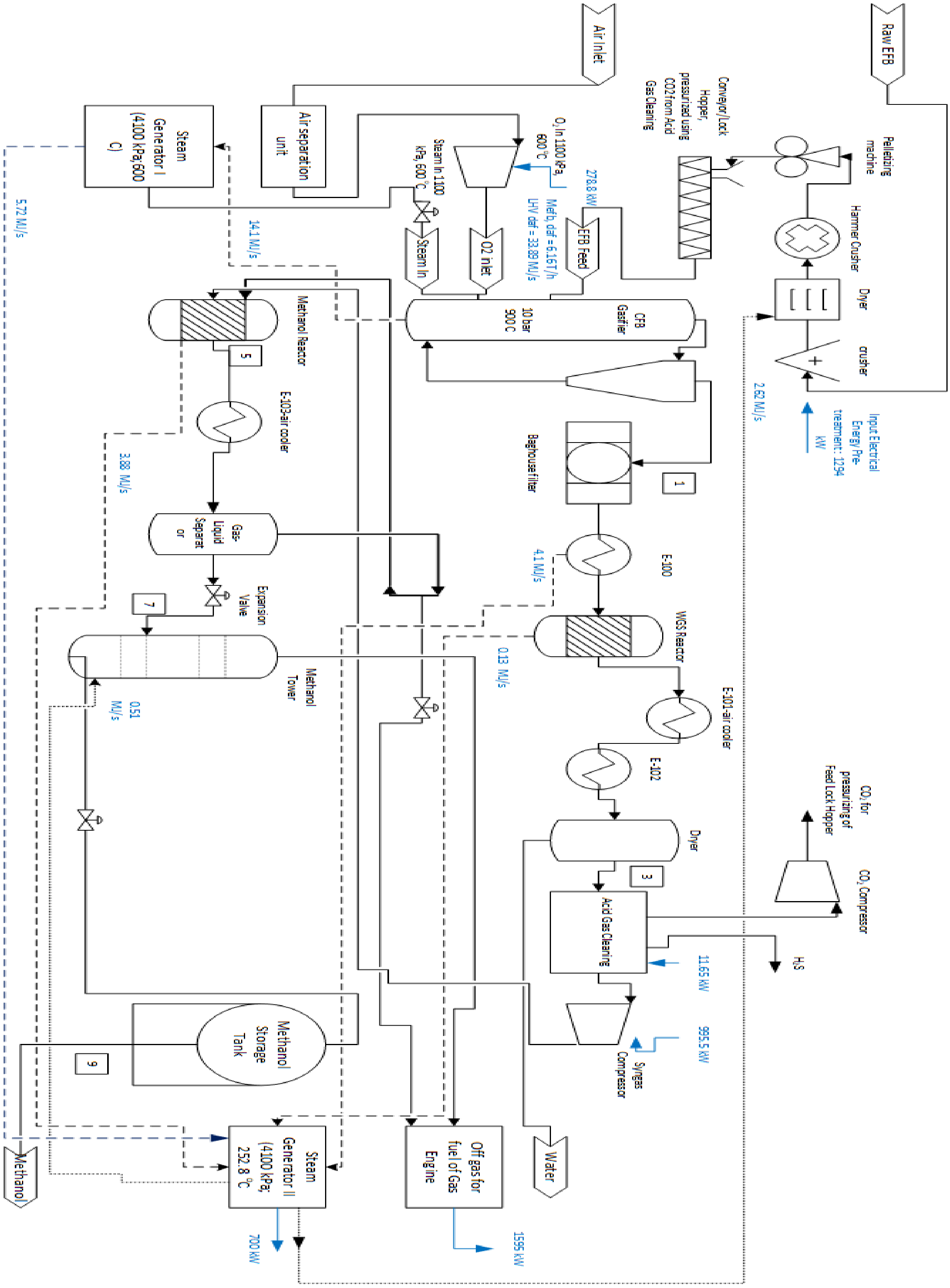

Figure 1. Process flow diagram of the methanol plant

3. Result and discussion

3.1. Process simulation result

The simulation result on every stream number shown on figure 1 was presented on table 1 results showed the total mass and molar flow, operating temperatures, operating pressures, heat flow, and composition of each substance produced.

Table 1. Stream composition of methanol plant

Stream No.		1	3	5	7	9
Vapour Fr.		0.9932	1	1	1	0
Temp	C	900	25	200	58.19	35
Pressure	kPa	1 000	997	5 000	1 000	100
Molar Flow	Kgmol h^{-1}	602	683	798	177	164
Mass Flow	kg s^{-1}	3.17	3.58	5.50	1.59	1.45
Heat Flow	MJ s^{-1}	-11.41	- 23.41	- 32.42	-11.93	-9.56
Mole Frac (%)						
H_2		35.09	48.80	14.49	0.18	0.00
CO		48.47	24.77	15.52	0.28	0.00
CO_2		6.66	23.76	17.82	5.33	0.15
H_2O		6.46	0.34	0.08	0.34	0.37
CH_4		2.20	1.94	26.43	2.07	0.00
H_2S		0.19	0.16	0.00	0.00	0.00
N_2		0.26	0.22	3.35	0.12	0.00
CH_3OH		0.00	0.00	22.30	91.67	99.5

Raw methanol product represented by stream number 5. The stream then cooled and separated in Gas-Liquid separator, where gas product consists mostly of CO, CO_2, CH_4, H_2. The gas product recycled at 79 % mol and 21 % mol of the gas product was delivered and mixed with top product of Methanol distillation tower as off-gas. Off-gas was utilized as a fuel of ICE for power generation. The liquid product of Gas-Liquid separator was expanded from 5 000 kPa to 1 000 kPa, to follow the operating condition of methanol purification section [9].

Stream number 9 was methanol product with purity 99.5 % since methanol is in liquid form at atmospheric pressure and at a temperature below 63.9 °C [29], it was stored in the atmospheric storage tank, by first reducing the pressure in stream 8 to atmospheric pressure (stream 9) by using pressure reducing valve. The tank equipped with a water cooling system to maintain Methanol temperature at 35 °C. The yield of methanol over input EFB for the model developed was 85 %. Table 2 shows the mass of EFB input and methanol output, and together with the energy of EFB input and energy of methanol output. Table 2 shows the energy efficiency of the methanol plant based on gasification of EFB and energy efficiency based on LHV. The total energy efficiency value is 85 %.

3.2. Power consumption and generation

The total electrical power demand of main unit and section in methanol plant was shown in table 3. It is shown that the electricity demand is dominated by consumption of ASU and EFB pre-treatment. Table 4 shows power generated from waste heat and off-gas to cater to the demand of the Methanol plant. There was shortage on the electricity generated if plant relies only on electricity from waste heat and off-gas only. The shortage itself was 1 122 kW. Hence additional genset shall be provided.

Table 2. Energy efficiency of methanol plant

Parameter	Unit	Value
EFB in	kg h^{-1}	6 160
LHV EFB in (daf, from HHV in [21])	MJ kg^{-1}	19.81
Methanol out	Kg h^{-1}	5 233
LHV Methanol out	MJ kg^{-1}	19.83
Energy in from EFB	MW	33.90
Energy out from Methanol product	MW	28.83
Energy Efficiency	%	85

Table 3. Power consumption of methanol plant

Plant Section/Unit	Power Consumption (kW)
Air Separation Unit	1 103
Syngas compressor	996
Pre-treatment EFB	1 294
Acid Gas Cleaning	11.65
CO2 compressor	12.35
Power Demand	3 417

Table 4. Power generation of methanol plant

Parameter	Unit	Value
Off-gas mass flow	kg h^{-1}	1 189
LHV off-gas	MJ kg^{-1}	12.71
Off-gas Energy flow	MJ h^{-1}	15 112
Electricity conversion efficiency [30]	%	38
Electricity from ICE	kW	1 595
Electricity from Steam Turbine	kW	700
Total Electricity from waste heat/energy	kW	2 295

Biggest power consumption was contributed by electricity generation for pre-treatment of EFB followed by Air Separation Unit (ASU). If the gasification intended only for power generation, only syngas required, and oxidant used is air [31]. Therefore power requirement will decrease significantly.

Methanol mass flowrate was 85 % of EFB biomass mass flowrate input. The overall energy efficiency of this model is 85 % for pre-treated EFB, and this is higher than the efficiency reported by [9], which gave 56 % to 58 % energy efficiency value, while in [9] mass of biomass inlet was unknown, only energy input of woody biomass was known. Energy efficiency in this study is not that far with the simulation study done by [6], which was showing energy efficiency at 77.7 %, and Methanol produced was 92% of coal mass flow rate input. If electricity is included in efficiency calculation, total energy efficiency became 92 %.

4. Conclusion

The model of methanol plant was designed and simulated by using Aspen Hysys. Simulation of the model was based on empty fruit bunch gasification that was conducted in CFB gasifier. The results of the simulation were more optimistic compared with references, especially for the yield of methanol and energy efficiency. Electric power for methanol plant based on EFB gasification was provided by excess heat, off-gas, and other type of fuel. Total electric power required is 3 417 kW, and 67 % of it fulfilled by waste heat steam cycle and off-gas ICE.

Methanol mass flow rate produced at 85 % of EFB feed mass flow rate. Energy efficiency from the simulation is 85 % for pre-treated EFB, and if electricity is included, total energy efficiency became 92 %.

The presented model is an example of decision for replacing fossil fuels by renewable resources, reducing global warming impact and moving from linear towards a circular economy. In the future study, developed methanol plant model based on EFB gasification will be used as a basis for techno-economic analysis and further, the presented model can be used as a reference to develop laboratory scale methanol production based on gasification of EFB.

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