

Modelling and Optimization of Torrefied Pellet Fuel Production

Ahmad Hafizi Awang*, Abdulhalim Abdulrazik, Azuin Mad Noor and Aainaa Izyan Nafsun

Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang, 26300 UMP, Gambang, Pahang, Malaysia

ABSTRACT

Torrefaction is a thermal process to convert biomass into a coal-like material, which has better fuel characteristics than the original biomass. Torrefied biomass has more energy density and hydrophobic which is superior quality for handling and storage. The objective of this research was to develop a simulation model of the torrefied pelletization process from empty fruit bunch (EFB). The process was simulated using ASPEN Plus. Optimization involved a selection of the model option that produced the maximum mass yield and minimum energy requirement, with a converged base case simulation as a starting point. Torrefied biomass pellet offered coal-like properties such as high heating value, brittle, high bulk energy density and more hydrophobic. These properties could potentially avoid costly power plant modifications. On the other hand, Malaysia has issued National Biomass Strategy 2020 with target to solve the problem of under-utilized biomass in this country. Base model was based on previous study. For optimization of mass yield and overall energy consumption, six model options of design configurations were analysed. Design model 0 was used as the base model. For design model 1, flue gas from combustion reactor was channelled to torrefaction reactor. For design model 2, flue gas from combustion reactor was split to dryer and torrefaction reactor. For design model 3, combustion reactor was removed. For design model 4, flue gas was channelled to dryer reactor without combustion reactor. For design model 5, flue gas separator after dryer was removed. Out of five options, results were tabulated for the optimum one. The results showed that the highest mass yield was achieved by simulation Model 5 at 90.76 % and lowest energy requirement was achieved by

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E-mail addresses:

hafiziawang94@gmail.com (Ahmad Hafizi Awang)

abdhalim@ump.edu.my (Abdul Halim Abdul Razik)

azuinmn@gmail.com (Azuin Mad Noor)

izyan@ump.edu.my (Aainaa Izyan Nafsun)

* Corresponding author

simulation Model 4 at 411.336 kW. Optimization result meanwhile had shown that Model 4 was selected because it gave the maximum profitability of RM 72834.45 by considering the yield and the energy consumption simultaneously.

Keywords: ASPEN Plus, empty fruit bunch (EFB), optimization, torrefaction and pelletization (TOP)

INTRODUCTION

Modelling and optimization of torrefied pellet fuel production from biomass have been a subject of interest in these recent years. In the production process, biomass undergoes torrefaction and pelletization stages to make renewable solid fuel. Torrefied biomass is a treated biomass that may be used as replacement of fossil fuel such as coal to generate electricity at coal-fired power plant in Malaysia. Torrefied biomass pellet has offered coal-like properties such as high heating value, brittle, high bulk energy density and more hydrophobic. After the biomass is torrefied it can be pelletized to ease handling and storage of the material. Prins et al. (2006) added that torrefied version of biomass created homogeneity which was an advantage for automated feeds environment.

Majority of scientists believe that human made carbon dioxide (CO₂) and other greenhouse gasses are one of the causes of global warming directly heating the atmosphere. In addition, we have been relying on fossil fuels for energy uses and this situation accelerates CO₂ productions through combustion process. Biomass is known to have the advantage of generating zero net carbon dioxide emission as a carbon neutral material (Novianti et al., 2014). On the other hand, Malaysia has issued National Biomass Strategy 2020 with target solve the problem of under-utilized biomass in this country (Melsson, 2013). Therefore, this study is in line with the national goal to increase the usage of biomass where torrefaction and pelletization of raw biomass are playing key roles. Emphases are given to the aspect of modelling and optimization.

Torrefaction of biomass has been widely commercialized in Canada and European countries (Hein, 2011); there are a few torrefaction and pelletization (TOP) plants have been established for example, the Toppel Energy in Netherland. The plants are well established but still need further improvement. Experiment works cannot be done especially when the plants are operating. Based on the study by Dudgeon (2009), to understand the process, process model simulation like ASPEN Plus is an important tool. Optimization can be conducted easily by simulation at lower cost with less time consumption and labour.

MODEL DEVELOPMENT

The main process in this torrefaction and pelletization is classified into three stages which consist of the crusher for size reduction, drying of the feed and the decomposition (torrefaction) of the feed. The torrefaction and pelletization flow sheet is shown in Figure 1. The Readlich-Kwong-Soave (RKS) cubic equation of state with Boston-Mathias alpha

function (RKS-BM) is used as a thermos-physical property method in the torrefaction process. RSTOICH reactor is used for reactor where the kinetics are unknown or unimportant, but stoichiometry and other information are known and RYIELD reactor is used for reactor where the stoichiometry and kinetics are unknown or unimportant, but yield distribution is known. The first stage is the crusher to form a pellet of raw empty fruit bunch (EFB) before transferring to the feed dryer. The cooling process can be done by blowing air through the pellet as they sit in the metal bin (Ciolkosz, 2009). Next is RSTOICH reactor which is used to simulate the drying of EFB feed to reduce the moisture content before torrefaction stage. When the dry EFB feed enters the RYIELD reactor, the decomposition of the dry EFB feed takes place and the feed is then converted into atoms of carbon (C), hydrogen (H), oxygen (O), sulphur (S), nitrogen (N) and ash. Part of crushed EFB and air entered the RSTOICH block for combustion reaction to produce the desired flue gas. Table 1 and Table 2 show the unit blocks used for the torrefaction model and the summary of unit operation. The proximate and ultimate analysis of all the feedstock used in this simulation model is shown in Table 3. 1000 kg/h raw EFB was used in this simulation process.

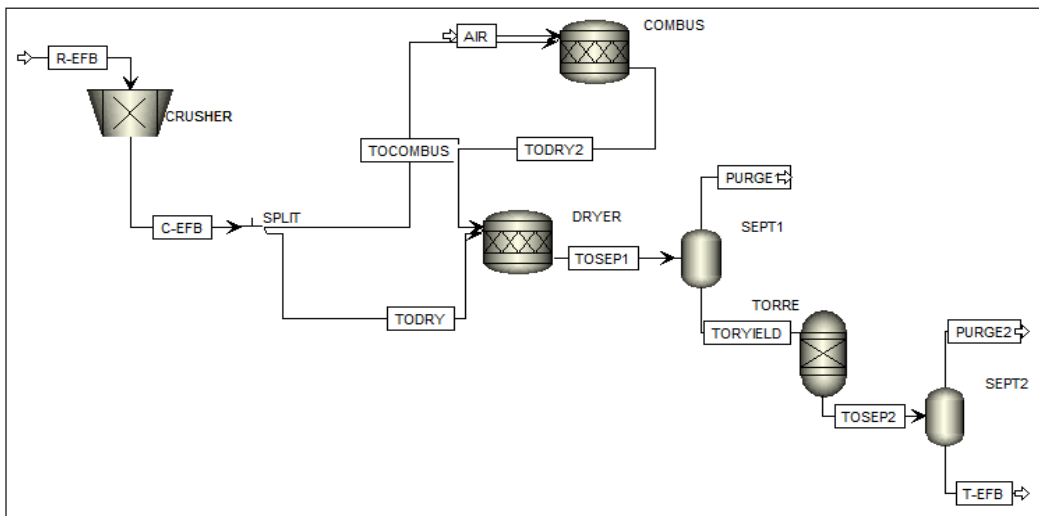


Figure 1. TOP process flow sheet

Table 1
Different unit blocks used for the torrefaction model

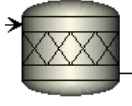
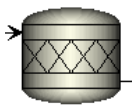
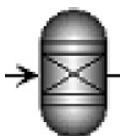
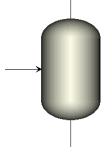
Block Name	Block Type	Block ID	Description	Reaction
COMBUS	RStoic		Combustion reactor - EFB is consumed to produce flue gas that will be used in drying reactor to reduce the energy usage in drying reactor based on mass balance	Feed → CO₂, H₂O, SO₂, N₂, Energy

Table 1 (continue)

Block Name	Block Type	Block ID	Description	Reaction
DRYER	RStoic		Dryer reactor - convert water in the biomass into moisture based on the extent of reaction.	Feed → 0.0555084H₂O
TORYIELD	Ryield		Yield reactor – convert non-conventional biomass into conventional components based on mass balance	(Feed) → C, H, O, N, S, ash
SEPT1 / SEPT2	Flash2		Separation of water and dry biomass	-

Source: Muslim, 2017

Table 2
Summary of Unit Operation

Name	Description	Value Input	Unit
CRUSHER	Crusher - Minimum particle diameter	10	mm
COMBUS	RStoich - Temperature - Pressure	240 1	°C bar
DRYER	RStoich - Temperature - Pressure	70 1	°C bar
SEPT1	Flash2 - Temperature - Pressure	160 1	°C bar
TORRE	RYield - Temperature - Pressure	240 1	°C bar

Table 3
Physical and Chemical Properties of EFB used in ASPEN modelling (Olisa, 2014)

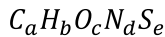
	Unit	Value
Proximate Analysis		
Moisture	15.00	% wt
Volatile	79.82	% wt
Fixed Carbon	13.31	% wt
Ash	6.87	% wt

Table 3 (continue)

	Unit	Value
Ultimate Analysis		
Carbon	43.80	% wt
Hydrogen	6.20	% wt
Oxygen	42.65	% wt
Nitrogen	0.44	% wt
Sulphur	0.44	% wt
Sulphur Analysis		
Pyritic	0.198	% wt
Sulfate	0.044	% wt
Organic	0.198	% wt

The Chemical Formula of EFB

In this simulation, EFB chemical formula was determined by formula based in Olisa (2014) study that can be written as $C_aH_bO_cN_dS_e$. The EFB chemical formula would be used in the RSTOICH reactor to balance the combustion, drying and torrefaction reaction. The calculation to obtain EFB chemical formula is as follows:



$$(Molecular\ weight) \times (Component) = (Ultimate\ analysis) \quad [Eq. 1]$$

$$(Component) = (Ultimate\ analysis) / (Molecular\ Weight) \quad [Eq. 2]$$

$$C: 12a = 0.438; \quad a = 0.037$$

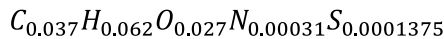
$$H: 1b = 0.062; \quad b = 0.062$$

$$O: 16c = 0.427; \quad c = 0.027$$

$$N: 14d = 0.0044; \quad d = 0.00031$$

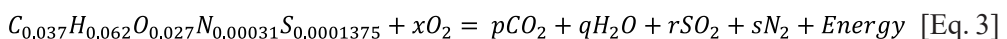
$$S: 32e = 0.0044; \quad e = 0.0001375$$

Therefore, the formula of the EFB can be written as:



Combustion of EFB in Combustion Reactor

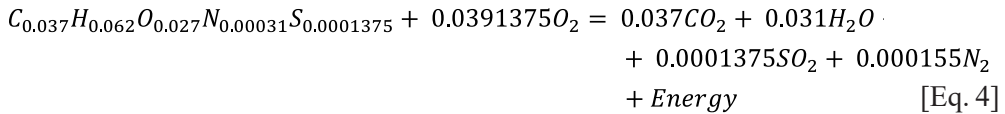
In combustion reactor, EFB is consumed to produce flue gas that will be used in drying reactor to reduce the energy usage in drying reactor. From a study conducted by Olisa (2014), a complete combustion will in theory produce only water vapour, carbon dioxide and other by-products. The combustion equation for EFB with oxygen thus become:



Balancing the equation given:

C: $1p = 0.037$;	$p = 0.037$
H: $2q = 0.062$;	$q = 0.031$
O: $0.027 + 1x = 2(0.037) + 0.031 + 2(0.0001375)$;	$x = 0.0375083$
N: $2s = 0.00031$;	$s = 0.000155$
S: $1r = 0.0001375$;	$r = 0.0001375$

Hence, the balanced combustion equation thus become:



Optimization

Process modelling and optimization problems are generally complex tasks, and hence computer software tools are essential for providing fast, reliable and user-friendly interface (Lam et al., 2011). In this paper, optimization to select the best structural configuration of TOP was modelled as mixed integer linear programming (MILP) with binary variables by considering the energy consumption and mass yield. In order to solve the developed optimization model, the General Algebraic Modelling System (GAMS) software version 24.9.2 was used.

Overall Methodology

The overall methodology for this paper is shown by Figure 2.

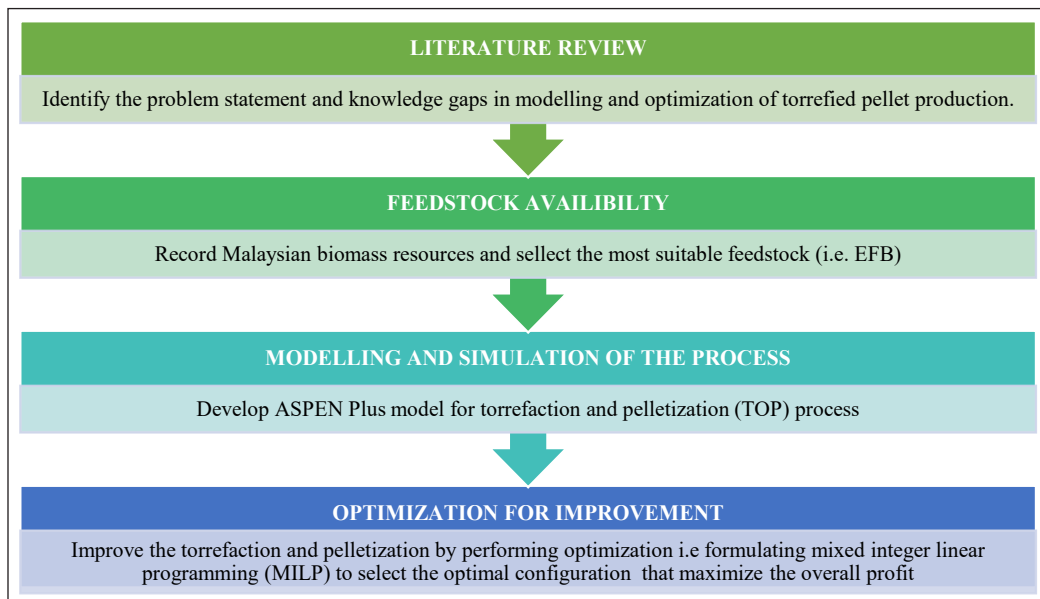


Figure 2. Overall methodology

Diagram for Structural Configurations

For optimization of the overall heat duty, different structure of simulation was studied to obtain the heat duty and compared with other simulation model. Design model 0 was used as the base model. For design model 1, flue gas from combustion reactor was channelled to torrefaction reactor (Figure 3). Therefore, the energy consumption of dryer would increase and for torrefaction would decrease. For design model 2, flue gas from combustion reactor would be split to dryer and torrefaction reactor (Figure 4). Therefore, the energy

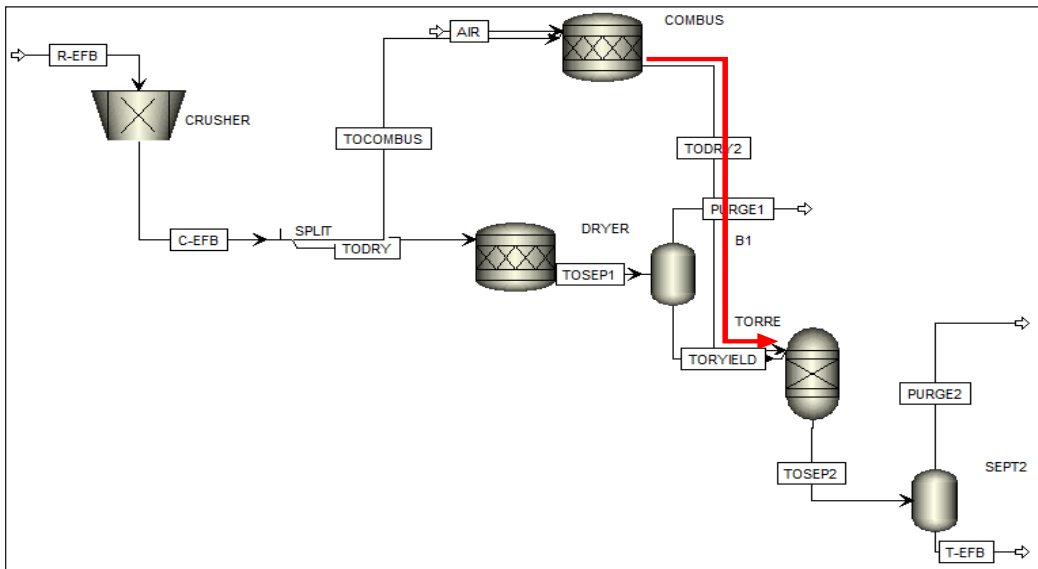


Figure 3. Simulation model 1

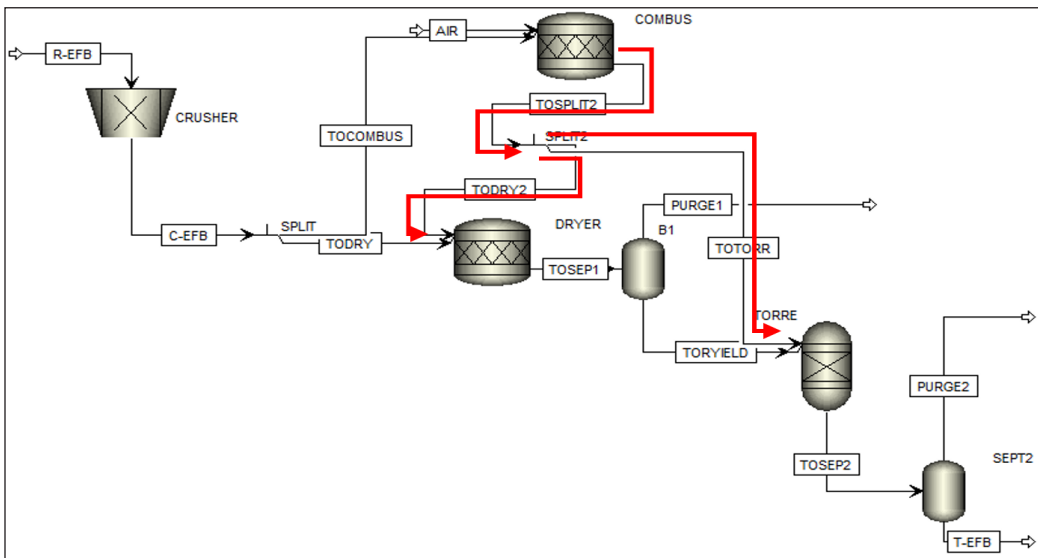


Figure 4. Simulation model 2

consumption for dryer and torrefaction would be reduced. For design model 3, combustion reactor would be removed (Figure 5). Therefore, the energy consumption for dryer would increase with no feedstock EFB used for combustion. For design model 4, flue gas was channeled to dryer reactor without combustion reactor (Figure 6). Therefore, the energy consumption at dryer would be reduced. For design model 5, Separator 1 was removed (Figure 7). Therefore, torrefaction process would include the flue gas from dryer reactor.

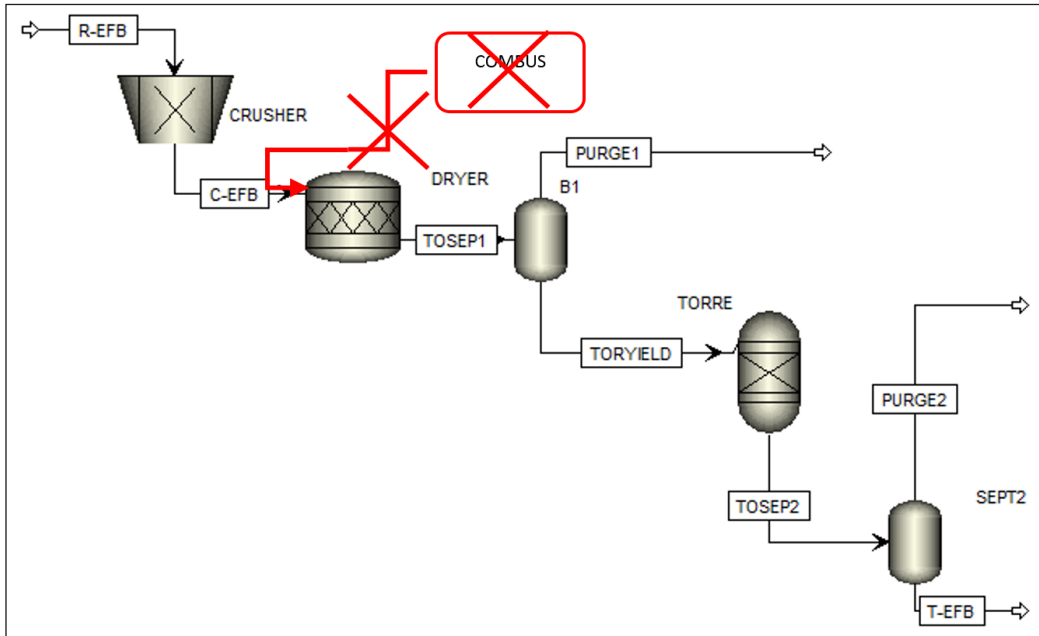


Figure 5. Simulation model 3

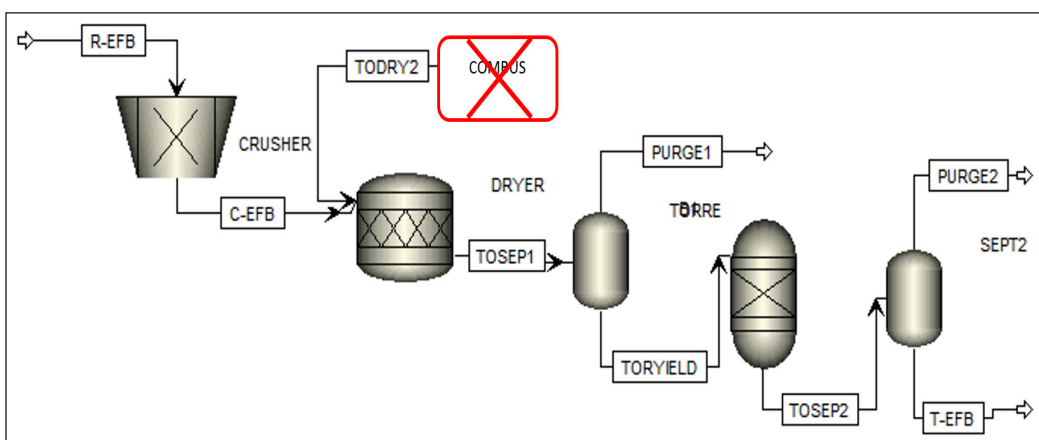


Figure 6. Simulation model 4

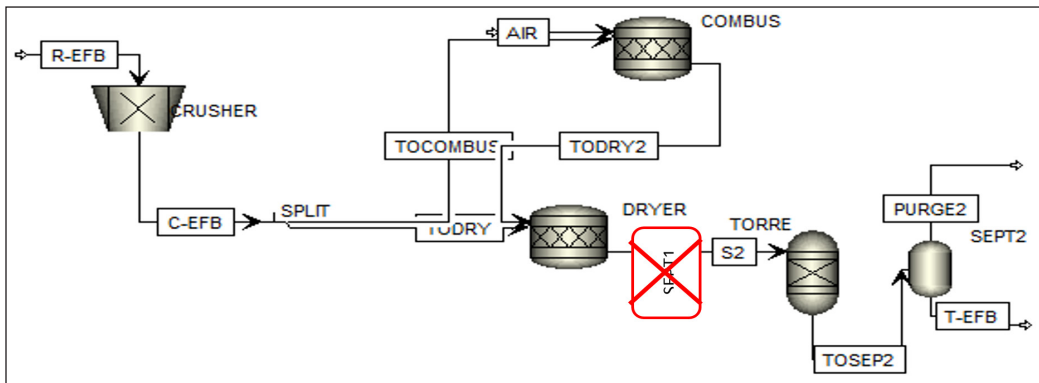


Figure 7. Simulation model 5

Formulation for Optimal Structural Selection

The formulation for the optimal selection was based on the overall profitability in an hour basis. The revenue, energy cost and raw material cost had been considered, while the other associated costs were neglected. For the formulation of the MILP, details as shown below;

Objective function:

Profit = Revenue – Energy Cost – Raw Material Cost

Revenue = Price of Torrefied EFB pellet * Flowrate

Energy Cost = Energy Consumption * Electricity Tariff

Raw Material Cost = EFB Flowrate * EFB Price

x_1 = Simulation Model 0

x_2 = Simulation Model 1

x_3 = Simulation Model 2

x_4 = Simulation Model 3

x_5 = Simulation Model 4

x_6 = Simulation Model 5

$$y = x_1(92010 - 13531.58 - 7000) + x_2(247230 - 53609.98 - 7000) + x_3(170130 - 1134.162 - 7000) + x_4(92010 - 33571.195 - 7000) + x_5(92010 - 12175.55 - 7000) + x_6(272280 - 43025.08 - 7000)$$

[Eq. 5]

Two constraints were identified; i) energy consumption limit, and ii) only one structural configuration would be selected. The energy consumption limit was 510 kW and this was calculated for about 30% of the typical parasitic load (JAREP, 2017). For the selection, 6 binary variables that represent each of the simulation were defined as $x_1, x_2, x_3, x_4, x_5, x_6$, which the value must be 0 or 1.

$$c_1: 457.148x_1 + 1811.148x_2 + 1134.162x_3 + 1295.61x_4 + 411.366x_5 + 1453.55x_6 \leq 510 \quad [\text{Eq. 6}]$$

$$c_2: x_1 + x_2 + x_3 + x_4 + x_5 + x_6 \leq 1 \quad [\text{Eq. 7}]$$

All the parameter that used in this formulation were obtained from (JAREP, 2017), and they are as followed:

Parasitic load	= 1.7 MW/h
Energy consumption limit	= 510 kW/h
EFB cost	= RM 7 / ton
TOP EFB cost	= RM 300 / ton
EFB usage	= 600 – 700 ton / day
<u>Electricity Tariff</u> , (Tenaga Nasional, 2018)	
TNB Pricing	= RM 29.60 / kWh

RESULT AND DISCUSSION

In biomass energy, torrefaction aims for the production of a fuel that is having improved properties compared to the original biomass. However, this should be achieved without losing too much mass due to release of volatile products during the treatment process. Therefore, the mass fraction is considered the crucial parameter in evaluating a torrefaction process. For the base model, 207.26 kg/h torrefied biomass was produced from 675.8 kg/h EFB feed to torrefaction reactor. The mass fraction yield of the torrefied biomass is defined according to Eq. (5) given as follows:

$$Y_{mass}(\%) = \left(\frac{\text{mass after torrefaction}}{\text{mass before torrefaction}} \right) \times 100 \quad [\text{Eq. 8}]$$

$$Y_{mass}(\%) = \left(\frac{207.26}{675.8} \right) \times 100$$

$$Y_{mass}(\%) = 39.99\%$$

Based on mass yield obtained, high mass reduction occurs due to high composition of volatile composition in feed EFB. High mass loss also occurs during drying stages where high moisture content is reduced before feed into torrefaction reactor.

The overall energy consumption was obtained from ASPEN Plus. Therefore, the overall heat duty for this base model simulation process was 457.1475 kW.

Simulation Result

The overall energy consumption for all simulation studied is compared as shown in Table 4.

Therefore, by comparing the total heat duty for different simulation model, model 4 has the lowest overall heat duty followed by the base model (Figure 8).

From Table 4, simulation model 4 has the lower energy usage at 411.336 kW. The difference of simulation model 4 and base model is that the flue gas is still supplied to the dryer reactor even combustion reactor is removed from the simulation model. This model is only applicable for industry that has already installed combustion reactor in their process with flue gas from existing combustion reactor channelled to TOP process dryer reactor.

Table 4
Summary of energy consumption for different simulation model

Unit Operation	Energy Consumption (kW)					
	Model 0 (Base model)	Model 1	Model 2	Model 3	Model 4	Model 5
COMBUS	-603.07	-603.07	-603.07	-	-	-603.07
DRYER	-253.079	-270.38	-261.73	-337.976	-2054.43	-253.079
SEPT1	93.0065	151.228	122.132	189.035	1021.21	
TORR	1386.92	2987.04	2186.98	1641.81	1641.81	3802.82
SEPT2	-166.63	-453.67	-310.15	-197.254	-197.254	-493.121
Total	457.1475	1811.148	1134.162	1295.615	411.336	1453.55

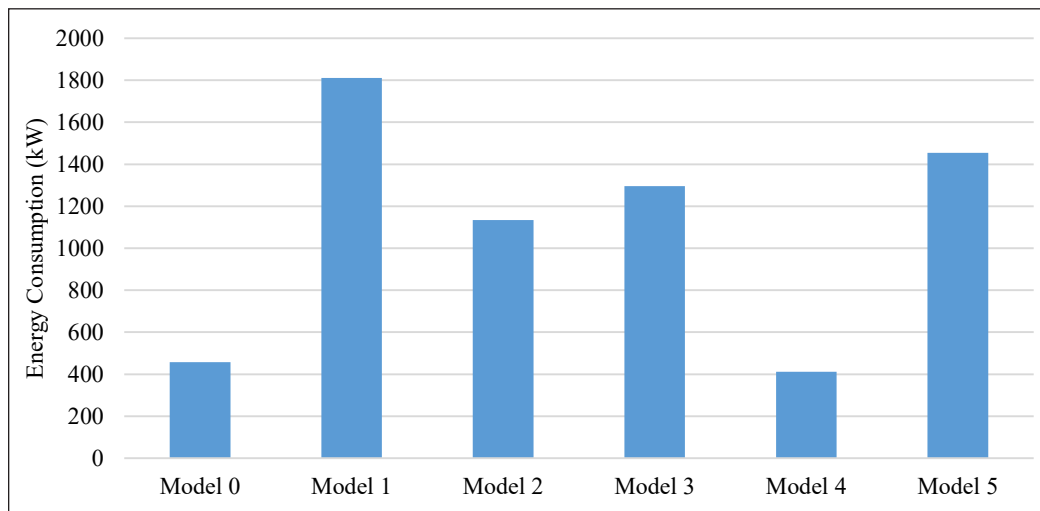


Figure 8. Overall energy consumption at different configuration model

The mass yield is different with different simulation model. The comparison of mass yield of torrefaction reactor is given in Table 5.

Table 5 and Figure 9 show the summary of mass yield for different simulation model and mass yield at different configuration model. For mass yield of torrefied biomass and untreated biomass, simulation model 5 had the highest mass yield at 90.76%. The difference of simulation model 5 and base model is that the flue gas separator after dryer reactor is removed before torrefaction reactor.

Table 5
Summary of mass yield for different simulation model

Simulation	Inlet (kg/h)	Outlet (kg/h)	Y_{mass} (%)
Model 0	675.801	207.255	30.67
Model 1	684.7506	564.276	82.41
Model 2	680.2753	385.766	56.71
Model 3	800	245.345	30.67
Model 4	800	245.345	30.67
Model 5	675.801	613.345	90.76

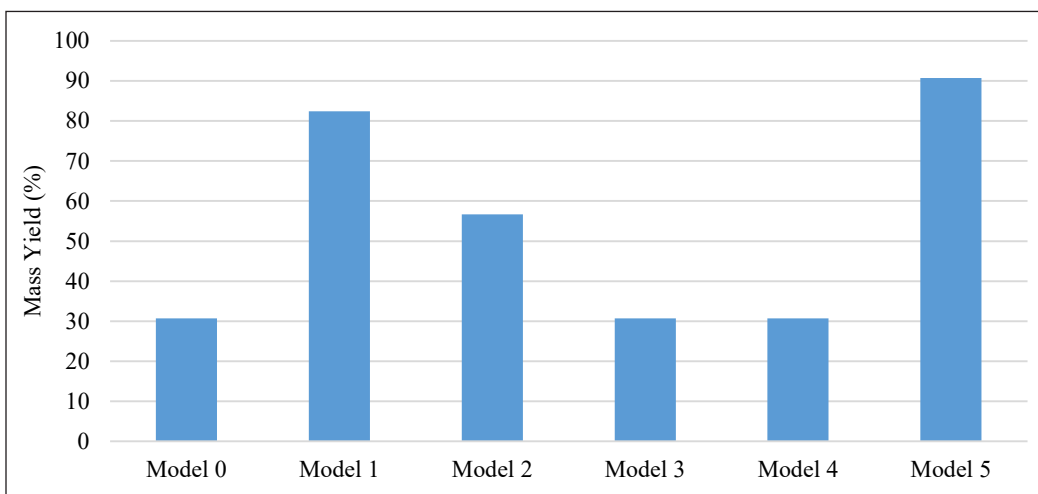


Figure 9. Mass yield at different configuration model

Optimization Result from GAMS

From the GAMS optimization result using CPLEX solver, one simulation model was selected by considering energy consumption and mass yield of TOP simultaneously. Simulation model 4 has been selected to be the best structural configuration with overall profitability of RM 72834.45.

CONCLUSION

In conclusion, the best simulation model should be selected by the simulation that has the lowest overall energy consumption and the highest mass yield of torrefied biomass and untreated biomass. For overall energy consumption, simulation model 4 has the lowest energy usage at 411.336 kW. The difference of simulation model 4 and base model is that the flue gas is still supplied to the dryer reactor even combustion reactor is removed from the simulation model. This model is only applicable for industry that already installed combustion reactor in their process, existing flue gas from the combustion reactor will be

channelled to dryer reactor. The simulation model 4 and base model show similar mass yield result of 30.67%. For mass yield of torrefied biomass and untreated biomass, simulation model 5 has the highest mass yield at 90.76%. The difference of simulation model 5 and base model is that the flue gas separator after dryer reactor is removed before torrefaction reactor. Therefore, torrefaction process will include the flue gas from dryer reactor. Based on previous study, it is theoretically impossible for mass yield to be higher than 70% where at least 30% of biomass is a volatile matter that will be removed during torrefaction process (Bergman, 2005). The comparison between simulation model 5 and base model in overall energy consumption is that simulation model 5 is using 1453.55 which is 996.4025 kW higher than the base model. Therefore the best simulation in this paper is simulation model 4 with the lowest overall energy consumption at 411.336 kW and acceptable mass yield at 30.67%. From the optimization result with GAMS and with consideration of both factors, simulation model 4 was selected to be the best structural configuration which can be possibly implemented in any thermal based biomass pre-treatment project.

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NOMENCLATURE

%	Percent	kg/h	kilogram per hour
%wt	Weight percent	kW	kilowatt
°C	Degree Celsius	kW/h	kilowatt per hour
bar	Bar (Pressure)	MILP	Mixed integer linear programming
C	Carbon	MW/h	Megawatt per hour
CO ₂	Carbon dioxide	N	Nitrogen
EFB	Empty fruit bunch	O	Oxygen
GAMS	General Algebraic Modelling System	S	Sulphur
H	Hydrogen	SO ₂	Sulphur dioxide
H ₂ O	Water	TOP	Torrefaction and pelletization
		Y _{mass}	Mass yield

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