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Technical and Economic Analysis of A Biomass Pyrolysis Plant

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Abstract

Bio-oil from fast pyrolysis of biomass has great potential to be one of the main renewable energy sources. At present, there are only a small number of commercial bio-oil plants because their operation is rather complicated and the return is not attractive. With funding from the government sector, a small biomass pyrolysis plant (capacity of 20-30 dm^3 of bio-oil per day) was built and operated in Phrae, Thailand. In this paper, practical stepwise methodologies were presented to technically analyze the production and energy consumption of bio-oil production based on the data from this demonstrated plant. Mass and energy balance calculations were carried out to assess the performance and improve process design. An economic analysis was also performed to study the potential of biomass-to-bio-oil conversion costs and viability of commercialization. From the investigation, it was found that the operation cost of crude bio-oil production was about 30-35 Thai baht per dm^3. Even though the operating cost of the fast pyrolysis units is excessively high under current situation, the biomass plant still has potential to generate attractive economic return if the upgrading process is employed as well as assistance from the government is available to subsidize the sale price.

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Keywords: Bio-oil; Thermochemical Conversion; Feasibility Analysis; Renewable Energy

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1. Introduction

Biomass is one of the major renewable energy sources in Thailand. The Thai Office of Agricultural Economics (OAE) listed many types of biomass that have potential to be promoted for energy application. Examples were fast growing trees or economic trees, (e.g. Eucalyptus), wood residues (e.g. Bark, and Sawdust). Sawdust from the furniture factory sector was identified to have potential to be a major

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renewable energy resource for Thailand [1]. There are various technologies for biomass conversion [2-8]. Bio-oil from fast pyrolysis is one of a number of renewable energy sources that converts biomass to higher value products [9].

With funding from the government sector, a small biomass pyrolysis demonstration plant was built and operated in Phrae, Thailand. Fluidized bed pyrolysis technology was employed at 10-20 kg/h using sawdust from wood furniture industry. The base feed cost was 1,000 Thai baht (THB)/ton or only 1 THB/kg. The system was designed to operate at 8-10 h/day and managed by Earth and Sun Alternative Energy Co., Ltd. The pictures and process design of the plant are shown in Fig. 1.

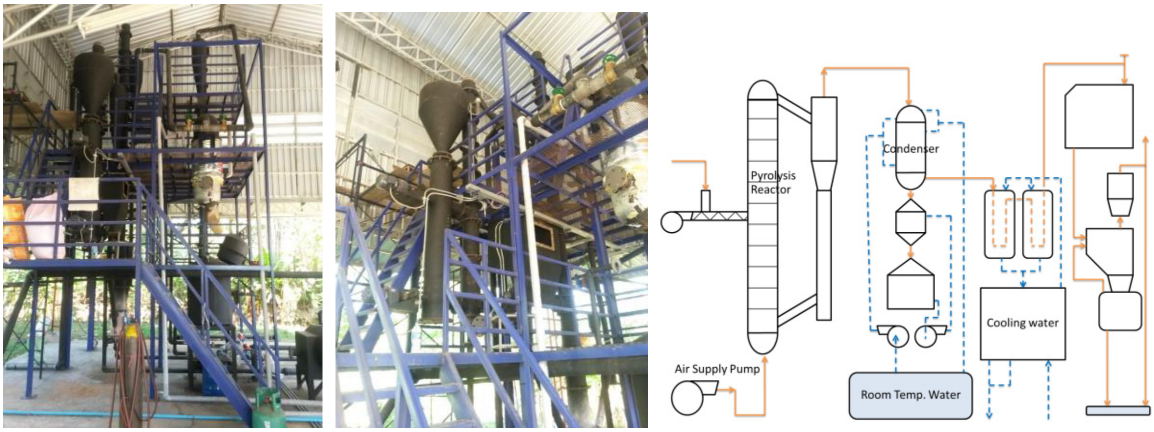

Fig. 1. Layout and process flow of the pyrolysis plant

Sawdust was feed from the left side of process flow to the pyrolysis reactor, heated up by combustion charcoal from the bottom. Bio-oil and other products were generated in gas phase. Pyrolysis transforms sawdust into (i) a bio-oil (ii) a synthetic gas, and (iii) a charcoal substance. All products moved to various sections to be separated and collected as shown in solid lines. Dotted line shows the cool water loop to condense products. In this work, mass and energy balance as well as economic analysis of the pyrolysis plant producing 25-35 dm^3/day of bio-oil were carried out. The finding can be used as the guideline to optimize and improve operation of this plant.

2. Methodology

Mass and energy balance were used to technically analyze the production and energy consumption of bio-oil production based on the data from the demonstrated plant. These calculations provide the theoretical basis for actual production and help improve economic effectiveness [10]. Mass balance is fundamental to the control of processing, particularly in the control of yields of the products [11]. While energy balance will optimize the operation cost and manage energy that being used, wasted or lost. To resolve the mass balance for the biomass to bio-oil plant, the unit operations of the block flow diagram from the process in Fig. 2 must be defined.

2.1 Mass and energy balance

Fig. 2 shows all inputs and outputs at the system boundary. Mass of processes was explained by total mass equation as [3]

$$m_{stored} = m_{out} - m_{in} \tag{1}$$

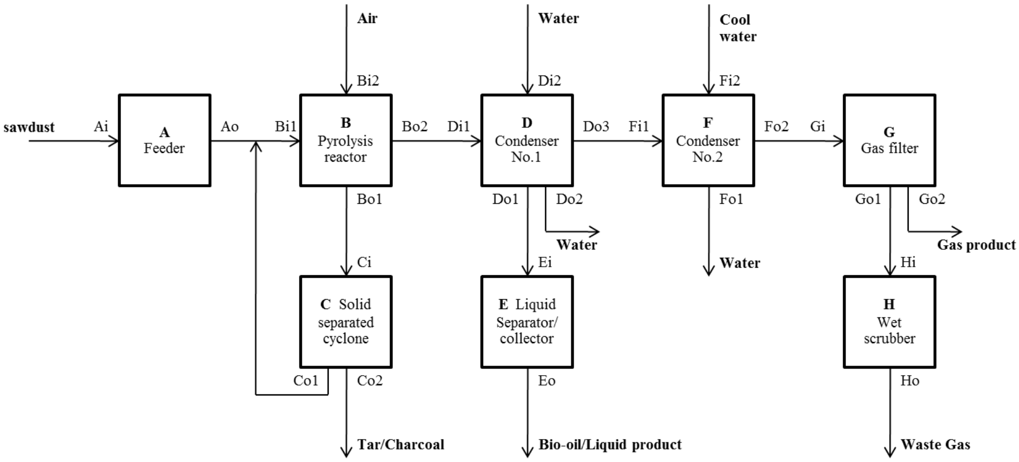

Fig. 2. Mass flow diagram

The mass balance calculation method [12] was performed as the derivation of simple expressions for the total syngas mass and the total pyrolysis liquid mass are

$$x = (G_s + L_s)/(D - C + M) \tag{2}$$

$$G = G_s/x = G_s(D - C + M)/(G_s + L_s) \tag{3}$$

$$L = L_s/x = L_s(D - C + M)/(G_s + L_s) - M \tag{4}$$

where nomenclature are dry mass of feed (D), mass of moisture in feed (M), char mass yield (C), syngas mass yield (G), liquid mass yield (L), syngas sample mass (G_s), liquid sample mass (L_s), and unknown fraction sampled of total gas phase mixture (x).

This can be seen to be logical, as splitting the total volatile mass released through pyrolysis in the proportion of gas to liquid in the sample taken, with an adjustment to the liquid yield for the moisture present in the feed. A batch production process was used in the biomass pyrolysis demonstration plant and in the pyrolysis of 30 kg of sawdust. All collected and forecasted data are shown in Table 1. Mass flows in this work include raw materials, air, products, wastes gas, char, and stored materials. It is difficult to directly carry out mass calculations because it is a complicated reaction process and there are numerous byproducts. Table 1 shows different products in a typical project.

The composition of the pyrolysis products were from different batches at different times. Gas product was estimated from different inputs, solid and liquid products [11]. For energy balance, energy streams in and out of the pyrolysis system were considered in the control volume. This pyrolysis plant is regarded as a closed system, with total heat equation as

Table 1. Collected and forecasted for mass balance calculation per batch

Item	Collected	Forecasted
Solid feed	Sawdust 30 kg, char coal 5 kg	-
Liquid feed	Chilled water, Room temp. water	-
Gas feed	-	Air 13 m^3/batch
Energy feed	*calculated from char coal	-
Electric energy feed	Air pump 0.75 kw, water chiller	Cap. 75% air pump
Solid product	8-10 kg of char and solid waste	-
Liquid product	10-12 kg	30% oil, 70% wood vinegar
Gas product	-	*calculated

$$\Delta Q = Q_{out} - Q_{in} \tag{5}$$

The energy flows of process include energy of raw material, the heat absorbed by sawdust during preparation process, chemical energy of pyrolysis, energy of all products, operation heat, and heat loss [13]. The heat calculation is based on the technical data from [14-16]. The approximate chemical equation for the pyrolysis of sawdust in this work was defined as

$$2CH_{1.44}O_{0.66} + 0.94O_2 \rightarrow CH_{1.9}O_{0.7} + 0.49H_2O + CO_2\ (+\,heat) \tag{6}$$

The activation energy of biomass in pyrolysis was reported to be around 70-100 kJ/mol [17]. Both energy input and output were evaluated using appropriate heating values. These represent the energy content for the starting materials and products. The following convection-conduction heat transfer was selected to perform with the collected temperature data.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla(-k\nabla T) = \rho C_p v \nabla T \tag{7}$$

2.2 Economics analysis

Operation cost, payback period (PBP) and break even analysis are used to investigate the relationships between the planned project cost and the rate of return. The breakeven point (BEP) is the point at which total cost and total revenue are equal, which means there is a balance of the profit and loss. BEP was defined as

$$BEP = \frac{AFC}{AR - ATOS - ACC} \tag{8}$$

It was used to determine the minimum output that must be exceeded in order to make profit with annual fixed cost (AFC), annual revenue (AR), annual tax on sales and addition (ATOS), and annual controllable cost (ACC) [15].

To determine the product value per volume of naphtha and diesel, a discounted cash flow analysis is used after determining the major three costs areas: (i) total project investment, (ii) variable operating costs, and (iii) fixed operating cost. Capital costs for bio-oil from biomass pyrolysis production are estimated at 5.1 million THB with a fuel yield of 8,250 – 11,550 dm^3 of products per year. The remaining fixed operating costs were calculated as percentages of the total labour cost or capital costs. Overhead cost was 60% of labor, and maintenance was about 2% of equipment. The economic viability of the process was evaluated using a discounted-cash flow-rate of return (DCFROR) calculation. An internal rate of return (IRR) of 10% was specified for a plant life of 20 years and straight-line depreciation over 10 years [16]. Working capital was estimated at 5% of the fixed capital investment. Operating costs were projected for both variable and fixed operating costs. Variable operating costs were determined from the material and energy balance.

Table 2. Analysis parameters for the small pyrolysis plant

Parameter	low-risk case	base case	high-risk case
Biomass cost (THB/kg)	0.6	0.8	1.2
Bio-oil yield (%)	30	33*	45
Bio-oil value (THB/kg)	20	25	30
Bio-oil expected BEP (%)	60	75	90

* based on current data

The basis for the capital, operating costs, product yield, product value as well as the financial calculations were addressed in three case; base, low-risk, and high-risk cases as shown in Table 2. Fixed operating costs include maintenance, taxes and insurance. They were forecasted and determined. Selling costs as crude bio-oil was collected and predicted; based on the previous study due to the lack of data.

3. Result and discussion

3.1 Technical analysis

From the mass balance, yields of products from the process were 35-40% as liquid product (30-35% of bio-oil and 5-10% of water and others), 40-45% as gas products, and 15-25% as char. Average yield of bio-oil from other plants and studies was about 50-75%, depending on the raw material and process [12]. The statistical analyses of the composition of the pyrolysis products from different batches and at different times were 2.1043-2.5910 of standard deviation and 0.6324-0.8225 of standard error mean.

Energy balance was estimated from the heat feed and consumption of the process. A Sankey diagram (Fig. 3a) shows the path way of energy in process. Heat input included electric energy was analyzed. Electric energy was transformed to thermal energy and electric energy losses, energy from biomass and charcoal was change to products energy and its losses. It was found that heat losses from bottom to top of the reactor were about 28-35%. This amount of losses affected directly to product yields. The amount of liquid products was slightly lower than the theoretical and designed values.

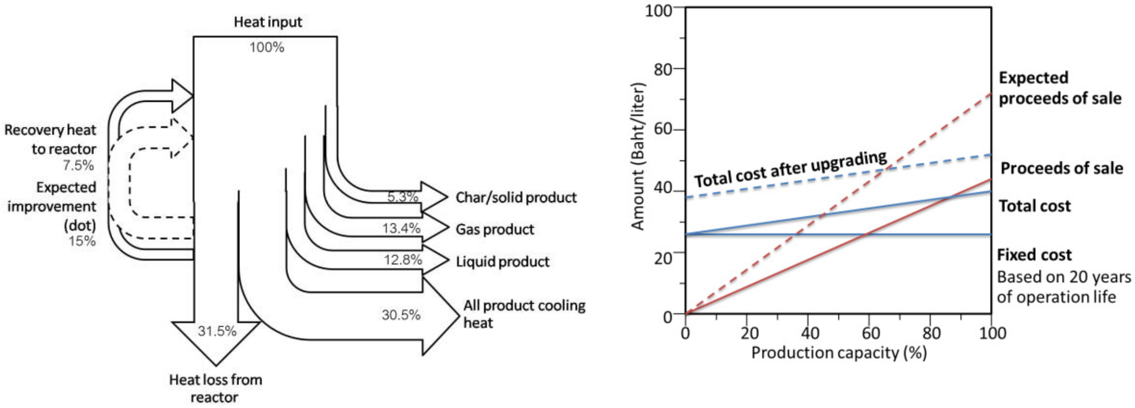

Fig. 3. (a) Sankey diagram of heat balance (b) Break-even analysis

3.2 Financial balance

The bio-oil production cost was estimated to be about 30-35 THB per dm^3. The estimated crude bio-oil price from other plants was 15-20 THB per dm^3 for the 100 kg/h plant. The capacity of plant effects directly to production cost. The results show that when the sale of project reaches 86.5% of the predicted value, payback period of plant is about 7.5 yrs, which is much shorter than the operational life. Unfortunately, the sale of the bio-oil has not yet reached the expected point.

Fig. 3b shows the break even analysis for the pyrolysis plant. A breakeven point based on the projection proceeds of sale and expected proceeds of sale after upgrading. Even though operation cost of bio-oil with upgrading will increase, higher proceeds of sale will reduce the production capacity to 66.5%.

There are a number of barriers that must be overcome to generate attractive economic return of this bio-oil plant. First, the amount of heat lost in process to reduce the operation cost, and also product yield improvement should be considered as a key variable for the bio-oil-production scenario. The cleaning equipment of the current pyrolysis device removes tars. The bio-oil upgrading process should be established to add more value to bio-oil. Collaborative activities with the government sector should continue with both technology and budget support to establish long-term access to this resource. Moreover, for long term development, bio-oil applications in burners, power generation or vehicle and the environmental issues should be studied.

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References

[1] Q. Wei, Y. Qu, T. Tan, "Mass and heat balance calculations and economic evaluation of an innovative biomass pyrolysis project", *Frontiers of Chemical Science and Engineering*, 5(3), 2011, pp. 355-361.

[2] N. Tippayawong, C. Chaichana, A. Promwungkwa, P. Rerkkriangkrai, "Gasification of cashew nut shells for thermal application in local food processing factory", *Energy for Sustainable Development*, 15, 2011, pp. 69-72.

[3] N. Tippayawong, C. Chaichana, A. Promwungkwa, P. Rerkkriangkrai, "Investigation of a small biomass gasifier – engine system operation and its application to water pumping in rural Thailand", *Energy Sources Part A*, 35, 2013, pp. 476-486.

[4] T. Wongsiriamnuay, N. Tippayawong, "Product gas distribution and composition from catalyzed gasification of mimosa", *International Journal of Renewable Energy Research*, 2, 2012, pp. 363-368.

[5] T. Wongsiriamnuay, N. Kunnang, N. Tippayawong, "Effect of operating conditions on catalytic gasification of bamboo in a fluidized bed", *International Journal of Chemical Engineering*, Article ID 297941, 2013, pp. 1-9.

[6] P. Khongkrapan, P. Thanompongchart, N. Tippayawong, T. Kiatsiriroat, "Microwave plasma assisted pyrolysis of refuse derived fuels", *Central European Journal of Engineering*, 4, 2014, pp. 72-79.

[7] P. Sittisun, N. Tippayawong, D. Wattanasiriwech, "Thermal degradation characteristics and kinetics of oxy combustion of corn residues", *Advances in Material Science and Engineering*, Article ID 304395, 2015, pp. 1-8.

[8] K. Chaiwong, T. Kiatsiriroat, N. Vorayos, C. Thararax, "Biochar production from freshwater algae by slow pyrolysis", *Maejo International Journal of Science and Technology*, 6, 2012, pp. 186-195.

[9] K. Chaiwong, T. Kiatsiriroat, N. Vorayos, C. Thararax, "Study of bio-oil and bio-char production from algae by slow pyrolysis", *Biomass and Bioenergy*, 56, 2013, pp. 600-606.

[10] M. Ringer, V. Putsche, J. Scahill, "Large-scale pyrolysis oil production: a technology assessment and economic analysis", Technical Report of National Renewable Energy Laboratory/TP-510 -37779, 2006.

[11] F. Mei, M. Dudukovic, M. Evans, N. Carpenter "Mass and energy balance for a corn-to-ethanol plant", M.Sc. thesis, Washington University in St. Louis, 2005.

[12] P. Brownsorta, D. Dickinson, "Mass and energy balances for continuous slow pyrolysis of six feeds and production of biochar for characterisation", A publication of the Interreg IVB project Biochar: Climate Saving Soils, 2012

[13] S. Sinha, A. Jhalani, M. R. Ravi, A. Ray, "Modeling of pyrolysis in wood: a review", *Solar Energy Society of India Journal*, 10(1), 2000, pp. 41-62.

[14] A. A. Boateng, C. A. Mullen, L. Osgood-Jacobs, P. Carlson and N. Macken, "Mass balance, energy, and exergy analysis of bio-oil production by fast pyrolysis", *Journal of Energy Resources Technology*, 134 (4), 2012, 042001-1-9.

[15] M. Cottam, A. Bridgwater, "Techno-economic modeling of biomass flash pyrolysis and upgrading systems", *Biomass and Bioenergy*, 7, 1994, pp. 267-273.

[16] C. E. Gregoire, R. L. Bain, "Technoeconomic analysis of the production of biocrude from wood", *Biomass and Bioenergy*, 7, 1994, pp. 275-283.

[17] P. T. Williams, P. A. Horne, "The role of metal salts in the pyrolysis of biomass", *Renewable Energy*, 4, 1994, pp. 1-13.